SOIL PIPING IN A TEMPERATE HUMID CLIMATE

THE FLEMISH ARDENNES (BELGIUM)

Els VERACHTERT

Promoter:
Prof. J. Poesen
Co-promoters:
Prof. Dr. J. Deckers
Dr. M. Van Den Eeckhaut

Members of the Examination Committee:
Prof. Dr. G. Govers
Prof. Dr. G. Verstraeten
Prof. Dr. J. Diels
Prof. Dr. C. Bielders
Prof. Dr. J. Nyssen

Dissertation presented in partial fulfilment of the requirements for the degree of Doctor of Science

November 2011

ISBN 978-90-8649-457-6
D/2011/10.705/75

Acknowledgements

Four years of diligent work on the field, in the lab, in the office with colleagues or solitary behind my computer screen, … This book in front of you is not only the result of my research, but can also be read as a chapter of my life. Luckily, I didn't have to walk this road alone, but I enjoyed the support of many whom I'd like to acknowledge here.

My PhD gave me the chance to develop my scientific skills, but a lot of other competences (management, communication skills, …) as well. Therefore, I'm grateful to my supervisor prof. Jean Poesen for giving me this opportunity. Thank you, Jean, for being always available for feedback, for proofreading my texts and giving helpful comments. The same holds for my co-supervisors prof. Seppe Deckers and dr. Miet Van Den Eeckhaut. Seppe, your enthusiasm guided me into the world of soil science. I'd like to thank you for motivating me and for engaging me in ardent discussions. Miet's experience in the study area immediately set me on the right track for my own research. Miet, your help in the field and with data analysis, as well as your general advice, is highly appreciated!

Prof. Gert Verstraeten and Prof. Gerard Govers completed my supervisory committee. I am grateful for your good advice and inspiring discussions, which brought my research to a higher level. All jury members are thanked for your constructive comments which helped in improving the manuscript.

For the geophysical detection methods, I relied on the expertise of the Forschungszentrum Jülich (Germany). Sander Huisman is especially thanked for his work and help with writing the chapter about these measurements.

In de Vlaamse Ardennen werd ik opgevangen en ondersteund door enthousiaste mensen van het Steunpunt Erosie, het Agentschap voor Natuur en Bos (bedankt Johan Cordier in het bijzonder) en het Regionaal Landschap Vlaamse Ardennen. Ook een dankjewel aan de milieudiensten van de betrokken gemeentes en aan de boeren, buren en eigenaars van de velden om mij de nodige achtergrondinformatie te bezorgen en me toelating te geven om er te boren, graven, meten… Speciaal bedankt Michel Liagre, het waren vele maar aangename uren die ik op je weide in Kluisbergen heb doorbracht.

My thanks goes also to everybody who helped me with the fieldwork: Kristof , Wim, Koen, Willem, Bastiaan, Karolien P, Karolien V, Annemarie, Steven, Nils, Sarah,

Vikram, Estela, Juan, Manuel, Fons, Pieter, Karen, mama, papa, … Ook was het fijn om te kunnen rekenen op een hele groep technisch personeel voor hulp en aangenaam gezelschap op het veld en in het labo: Valentijn, Jos, Mustafa, Lore, Sabrina, Bjorn, Steven.
Tijdens de voorbije jaren werkten bovendien verschillende thesisstudenten (geografen en bio-ingenieurs) mee aan dit onderzoek: bedankt Nele K., Ruben, Wouter, Alexander, Steven en Nele W.! Niet alleen was het leuk om samen veldwerk te doen, jullie hebben mij (ook letterlijk) geholpen om dit onderzoek tot op de bodem uit te spitten.
Geen doctoraat zonder… computerproblemen, helaas. Gelukkig stonden Johan en Hilde dan voor me klaar. De administratieve rompslomp namen Marie-Rose, Annemie, Sofie en de anderen van het balie-team voor hun rekening. Bedankt om zo mijn werk te verlichten.

Even when the research didn't proceed easily, I always enjoyed coming to the Geo-institute thanks to the lovely atmosphere created by a bunch of great colleagues (I will not attempt naming everybody and risk forgetting someone). Thanks to all of you for the pleasant breaks, interesting discussions, nice dinners, parties, … Even as a outsider, I immediately felt part of the 'Geography family'. My office mates (Karolien V, Koen, Sarah, Karolien P., Ihab and Manuel) deserve special mention for raising my spirits whenever I needed it with nice conversations, 'healing' music and comfort food! ;-) Also, thank you Wim and Lien for being just one skype-message or a few offices away when I needed a chat. Estela, gracias por el apoyo y la amistad, no hubiera sido posible sin ti!

Aan mijn familie en vrienden: jullie steun en interesse, de lieve mails en telefoontjes, … waren een stimulans om te blijven volhouden. Bio-ir 'lotgenoten', Nele, Eline en Bart bedank ik voor de gezellige lunches en (overzeese) peptalk. Mama, papa, en Karen, het doet deugd te weten dat ik steeds op jullie kan rekenen! Bedankt, Karen, 'your word is as good as your bond'. Tot slot verdient ook Pieter, mijn grootste supporter, een bijzondere vermelding. Dankjewel om mij steeds aan te moedigen om door te zetten, maar om ook te zorgen voor de nodige ontspanning en zo mijn mentale gezondheid in de gaten te houden! ;-)

Els

Abstract

Collapsible loess-derived soils are prone to soil piping erosion, where enlargement of macropores may lead to a subsurface pipe network and eventually to soil collapse and gully development. This study aims at understanding the factors controlling spatial patterns of piping in loess-derived soils in a temperate humid climate. In order to map the spatial distribution of collapsed pipes (CP) and to identify the environmental controls on their distribution, a regional survey was carried out in a 236 km² study area in the Flemish Ardennes (Belgium). In total, 137 parcels with 560 CP were mapped. The subsurface erosion in these parcels causes significant soil losses (0.6 – 1.2 t ha^{-1} yr^{-1}) in a land use –pasture– that is typically considered to be non-susceptible to surface erosion. Standard geophysical detection methods turned out not to be successful yet in detecting subsurface pipes in silty soils that are not (yet) collapsed. To obtain information on the local soil characteristics controlling pipe development, 12 soil profiles covering parcels with and without CP were analysed in detail. Logistic regression and topographical thresholds were used to gather insight in the spatial distribution of the CP and to create susceptibility maps. Which conditions need to be met to induce piping in the Flemish Ardennes? A certain slope gradient in combination with a sufficiently large contributing area is needed, although the hydraulic gradient is more important than the surface slope gradient. Furthermore, the combination of loess-derived soils underlain by less-permeable clayey substrates favours the occurrence of high/perched water tables and gives rise to numerous springs. Other factors creating a concentrated water flow such as landsliding, road drainage or blocked/broken field drains, may add to a favourable hydrological situation for piping as well. In addition, many of the fields that match a steep topography and poor drainage are under pasture. This land use is the most favourable for biological activity by earthworms and small mammals. Anecic earthworm species enhance rapid vertical infiltration and mole burrows contribute to lateral flow in the soil profile. Preferential flow paths are generated and, with the necessary water supply and subsurface flow, can develop into pipes. Monitoring of pipe discharge, groundwater and precipitation revealed, although the fast responses of pipe discharge on rainfall events, the chemical composition of the pipeflow was most similar to the groundwater samples. Rain water mixes with soil water and groundwater and pushes pre-event water from the soil into the pipes by piston flow.

Samenvatting

Ondergrondse erosie door water of tunnelerosie (Eng.: piping, tunnelling) is niet onmiddellijk zichtbaar, waardoor dit erosieproces vaak aan de aandacht ontsnapt. Bij tunnelerosie worden ondergrondse lineaire holtes gevormd door stromend water wat kan leiden tot grondverzakkingen en discontinue ravijnvorming. Het onderzoek heeft tot doel meer inzicht te verschaffen in de ruimtelijke patronen van tunnelerosie in een 236 km² groot studiegebied in de Vlaamse Ardennen. Tijdens een intensieve terreinkartering werden in 137 percelen 560 instortingen door tunnelerosie (CP) in kaart gebracht. Daarbij leidt de ondergrondse erosie tot niet verwaarloosbare sedimentverliezen (0.6 – 1.2 ton ha^{-1} j^{-1}) in de weides met CP, en dit voor een landgebruik dat beschouwd wordt als ongevoelig voor erosie. Om de gevoeligheid van een locatie voor tunnelerosie te voorspellen, werd gebruikt gemaakt van logistische regressie. Een tweede gevoeligheidskaart voor tunnelerosie in het studiegebied kon opgesteld worden aan de hand van topografische drempelcondities van helling en toestroomgebied. Tunnelerosie komt vooral voor op plaatsen met de vereiste topografische index (voldoende steile helling in combinatie met groot toestroomgebied) en op hellingen met een concave kromming in plan en profiel, waar water samenkomt. De combinatie van loess bovenop minder doorlaatbare substraten bevordert het voorkomen van ondiepe watertafels en bronnen. De zones met een dunne homogene kleilaag (Lid van Aalbeke) in de ondergrond blijken dan ook het meest gevoelig voor tunnelerosie. Ook andere factoren die geconcentreerde afvoer stimuleren, zoals grondverschuivingen, drainage van wegen en kapotte velddrainage, kunnen bijdragen tot een hydrologische situatie die tunnelerosie bevordert. Daarenboven zijn veel velden op steile en natte hellingen weiland, het landgebruik met de hoogste biologische activiteit door regenwormen en kleine zoogdieren. Aangezien wormgangen van anekische wormen de verticale infiltratie en molgangen de laterale stroming bevorderen, kan verondersteld worden dat de biologische activiteit in combinatie met een voldoende hoge watertafel een belangrijke invloed heeft op de ontwikkeling van tunnelerosie. Monitoring van de ondergrondse stroming, grondwater en neerslag, toont de snelle respons van de stroming op neerslag. Nochtans komt de chemische samenstelling eerder overeen met grondwater dat bij voldoende neerslag verplaatst wordt naar de ondergrondse gangen.

Table of contents

List of symbols and abbreviations

A	upslope contributing area
A_p	mean cross section of a pipe
annual P	annual precipitation
ASM	antecedent soil moisture content
AUC	area under the ROC curve
CP	collapsed pipes
CP-grid cells	dataset of grid cells with collapsed pipes used for logistic regression
CP-parcels	pastures with collapsed pipes
CS model	complete sample model
D	depth of collapsed pipe
d	pipe diameter
DEM	digital elevation model
EC	electrical conductivity
EMI	electromagnetic induction
ERT	electrical resistivity tomography
FZ	groundwater fluctuation zone
GPR	ground-penetrating radar
H	hydraulic head
h	height of the pipe
K_{sat}	saturated hydraulic conductivity
LS	landslide(s)
LiDAR	light detection and ranging
NCP	no collapsed pipes
NCP-grid cells	dataset of grid cells without collapsed pipes used for logistic regression
NCP-parcels	pastures without collapsed pipes
P	measuring period (yr)
PET	potential evapotranspiration
PS model	partial susceptibility model
Q_s	sediment load (pinhole test) (g s^{-1})

Q_w	pipeflow discharge (pinhole test) (cm^{-3} s^{-1})
ROC	receiver operating characteristic
S	slope gradient
SSL	subsurface soil loss (ton)
SSLR	subsurface soil loss rate (ton/ha/yr)
st dev	standard deviation
StA	size of study area
SWT	summer water table
TDS	total dissolved solids
TOL	tolerance
V	volume of collapsed pipes (calculated per parcel)
V_{cp}	volumes collapsed pipes
V_p	volume pipes
VIF	variance inflation factors
w	base width of the pipe
WWT	winter water table

Chapter 1
Introduction

1.1. PROBLEM STATEMENT

Soil erosion has an important impact on soil quality, which can result in severe land degradation. The removal of topsoil decreases soil fertility and crop yields by inducing loss of plant nutrients and essential soil components such as humus and colloids (Boardman and Poesen, 2006). Soils in the Belgian loess belt are intensively cultivated and seriously affected by physical degradation and water erosion as well. Extensive knowledge exists on sheet and rill, gully and tillage erosion on these loess-derived soils (e.g. Gabriels et al., 1977; Poesen and Govers, 1994; Poesen et al., 1996; Nachtergaele et al., 2001; Poesen et al., 2003; Vanwalleghem et al., 2005). More recently, erosion due to crop harvesting (e.g. Ruysschaert et al., 2004; Ruysschaert et al., 2008) and landslides (e.g. Ost et al., 2003; Van Den Eeckhaut et al., 2007a) were investigated. However, less is known about subsurface soil erosion processes or piping erosion in this area. In the Flemish Ardennes, damage from soil collapse after subsurface erosion is reported by farmers as well as residents facing soil collapses next to their houses. Pipe collapses mostly hamper farmers' activities and in a few cases even threaten the stability of buildings. Problems related to soil erosion in the Flemish Ardennes are reported in an inventory of *Provinciaal Centum voor Milieuonderzoek* and the municipalities (Lijst erosieknelpunten 2007, Steunpunt Erosie – Provincie Oost-Vlaanderen). All communities within the study area make mitigation plans in order to decrease sheet, rill and gully erosion. Unfortunately, mitigation measures against pipe collapse are not included in these plans, because information on this degradation process is still lacking.

Similarly, piping erosion is the 'neglected' erosion process at the European scale as well. The Soil Thematic Strategy, one of the seven Thematic Strategies of the European Commission, and several projects dealing with land degradation (e.g. RECONDES, DESIRE) indicate that soil erosion is recognized as an important problem in Europe, but no attention is paid to subsurface erosion. For many years, research on soil erosion was mainly focussing on sediment detachment and transport in overland flow while subsurface flow erosion was regarded as a process of limited importance restricted to certain materials (Bryan and Jones, 1997). Since the 1960s an increasing evidence of the impact of subsurface flow on storm hydrographs and the increasing reports of subsurface erosion features in many different materials and climatic zones led to an increasing interest in subsurface flow and related soil erosion processes (Bryan and Jones, 1997). Based on the distribution of three piping-prone soil types (Gleysols and Histosols, collapsible Luvisols and dispersive Xerosols), Faulkner (2006) estimated the area of the land seriously at risk from piping erosion in the EU to exceed 260 000 km² (8 % of European member states before 2004). In clear contrast, however, is the limited information about the temporal and spatial factors controlling subsurface erosion.

Nevertheless, there are many problems associated with piping erosion. Piping acquired important relevance in civil engineering, as earth dam failures due to piping have occurred since the earliest dams were constructed around 2900 BC (Richards and Reddy, 2007). Piping or internal erosion is also included as one of the dike failure mechanisms in Dutch as well as Flemish reports (e.g. IMDC, 2006; Silva and van Velzen, 2008; Van Hoestenberghe et al., 2010). Piping with which civil engineers are most familiar is a direct result of human-induced changes in hydraulic head in the groundwater system at a construction site. However, exactly the same type of piping may develop without man's interference (Parker, 1963). Earth bank failures and subsequent gully formation due to piping are one of the most reported problems (e.g. Poesen et al., 1996). Wilson (2011) suggests that ephemeral gullies can be misinterpreted as being caused by convergent surface flow if observations are made after the runoff event (instead of when flow is first established through soil pipes). Also seepage undercutting leading to riverbank collapse is widespread (e.g. Wilson et al., 2007; Cancienne et al., 2008), although its complexity and interactions with other processes tend to mask the effects of piping (Hagerty, 1991a; 1991b). Besides gullying, piping has also been found to be both a cause and a result of landsliding (e.g. Uchida et al., 2001; Hardenbicker and Crozier, 2002). Pipes can play a role in hillslope sediment delivery, but also in the transport of nutrients and distribution of contaminants (e.g. Krothe et al., 1999). Most relevant for this dissertation is the land degradation due to partial or complete collapses of pipe roofs on hillslopes. Being partly hidden, this erosion process can be well advanced before roof collapse reveals the size of the pipes. Moreover, pipe collapse in some loess areas (e.g. Bonn area in

Germany, Flemish Ardennes in Belgium) has mainly been observed in pastures, a land use that is traditionally considered to be not susceptible to surface erosion by water.

1.2. PIPING EROSION

1.2.1. The process of piping in soils

Piping or tunnel erosion is a process involving the hydraulic removal of subsurface soil, causing the formation of underground channels in the natural landscape (Boucher, 1990). The dominant process in piping is mechanical rather than solutional erosion, also expressed with the term ‘pseudokarst’ (Jones, 1981). Piping intensity reflects a critical interaction between climatic conditions, soil characteristics and local hydraulic gradients (Bryan and Jones, 1997). Generally three stages in tunnel development can be distinguished (Boucher, 1990).

In the initial stage, flowing water causes particles to detach from the soil matrix. Two types of subsurface erosion can cause this. The first occurs when water seeping through a porous soil has a sufficient drag force to entrain material through liquefaction or Coulomb failure, often referred to as spring sapping or *true piping* (Dunne, 1990) in the engineering sense. It can produce a subsurface conduit that works back from the outlet, often developing a complex branched network (Terzaghi and Peck, 1966). The second process involves expansion of an existing conduit or macropore due to the shear stress exerted by flowing water, including the enlargement of animal burrows, root channels or soil cracks. This process has often been distinguished as *tunnel erosion* or *tunnelling*, although it is also referred to as piping in much of the literature. Bryan (2000) acknowledges that piping and tunnelling represent distinct erosional mechanisms but notes that both processes are often functionally indistinguishable and generally grouped under the term piping. This will be done in this study as well. According to Bryan and Jones (1997), the main distinction between piping and tunnelling is that tunnel erosion features do not necessarily develop from the outlet and they do not necessarily involve high seepage pressures.

In the second, more advanced, stage, soil particles are transported to an exit point of the tunnel where a sediment fan can be formed (Vacher et al., 2004b). This requires a sufficient slope gradient to develop a hydraulic head to drive water through the soil and to cause failure of the soil matrix.

The third and last phase of pipe development involves the ultimate collapse of the soil, forming sinkholes (Boucher, 1990). The process is described in Fig. 1.1. Pipeflow can occur at more than one level and often follows three-dimensional interconnecting networks (Zhu, 1997; Holden and Burt, 2002). The networks may have more in common with a sponge than a river network and the active network can be very different in individual flow events, often because of temporary blockages (Zhu, 1997).

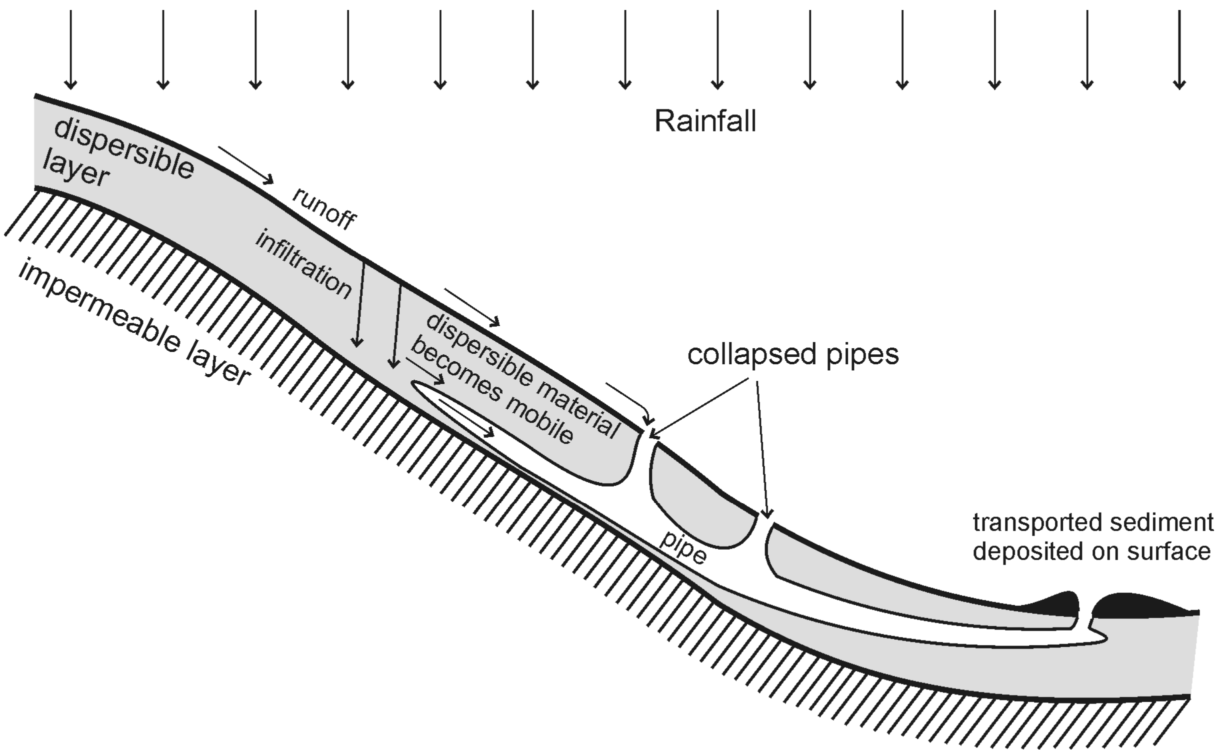


Fig. 1.1. Diagram illustrating the process of piping (after Boucher, 1990).

1.2.2. Factors controlling pipe development

No single factor or group of factors is universally responsible for the development of piping (Jones, 1981), but the initiating factors vary in different situations. Nevertheless, Parker (1963) provided a list of four essential factors: (i) enough water to saturate some part of the soil or bedrock above base level; (ii) sufficient hydraulic head to move the water through a subterranean route; (iii) the presence of a permeable, erodible soil or bedrock above base level; and (iv) an outlet. The basic conditions listed differ from those of Fletcher et al. (1954) mainly in that there is no requirement for the presence of an impermeable or retarding layer below the erodible layer. Some initiating factors of piping are repeatedly reported, while others seem to be specific for a certain environment.

Hydrological factors: water supply and drainage outlet

Obviously, a water source is needed for piping erosion, although its origin can vary. Some authors pointed to rainfall with a high variability in intensity (e.g. Gibbs, 1945; Farifteh and Soeters, 1999). Jones (1981) stated that for piping to occur, both periods of desiccation and periods of intense rainfall are needed. In a climate with distinct seasonality of rainfall, wetting and drying cycles have an important effect on the soil structure by structural collapse of soil exposed to evaporative drying and the formation of shrinkage cracks (Vacher et al., 2004b). These shrinkage cracks provide inlet areas for concentrated runoff flows through the surface soil horizon and expose dispersive subsurface clays to water, which can initiate pipe formation (Vacher et al., 2004b; Faulkner, 2006).

It is also generally accepted that there must be an outlet for drainage (Fletcher et al., 1954; Parker, 1963; Jones, 1981), located close to surface drainage networks (Farifteh and Soeters, 1999). The pipes require a suitable exit so that mobilised sediment can continue to be removed from the pipe (Vacher et al., 2004b). Water emerging from the exit of pipes is typically turbid, with a high suspended load which may be transported to local water courses, or can form a sedimentation zone downstream due to settling of the eroded material (Boucher, 1990; Vacher et al., 2004b). Pipe outlets mainly occur at gully and river banks, road cuts or at footslopes.

Topography: hydraulic gradient

Furthermore, a sufficient hydraulic gradient within the soil is required (e.g. Fletcher et al., 1954; Parker, 1963; Jones, 1981; Bryan and Yair, 1982; Farifteh and Soeters, 1999; Vacher et al., 2004b). For piping to occur on low slopes there must be either a plentiful supply of water, possibly seasonally, steep hydraulic gradients, which can be caused by an adjacent free-face or gully wall, or very favourable soil profiles (Jones, 1981). Although a considerable relative relief is necessary, the hydraulic gradient and not the surface slope gradient controls pipe development (e.g. Jones, 1971; Baillie et al., 1986). Where flow converges to a suitable lower hydraulic outfall, macropores are enlarged by subsurface erosion and will act as drains (Faulkner, 2006). If a landscape has sufficient relative relief for hydraulic gradients to be maintained as piping erosion proceeds, the enlargement of pipes can be rapid (Naidu et al., 1995; Sherard and Decker, 1976; Sumner and Stewart, 1982; Faulkner, 2006).

Lithology/soil

Soil texture

Considerable emphasis has been placed upon textural analyses in literature, despite the fact that properties such as structure, porosity, erodibility and drainage are of more direct relevance to the development of piping (Jones, 1981). Nevertheless, the best developed piping occurs in soils with high silt-clay content, which may favour piping by providing cracking potential, easily eluviated particles and stronger roofing to prevent destruction (Jones, 1981). Furthermore, the clay mineralogy plays a role in the susceptibility to piping of dispersive material (section 1.2.3.1). The specific mineralogy and the particular arrangements of the clay platelets will determine how 'active' they are in terms of physical changes (e.g. deflocculation) (e.g. Sumner, 1992; Sumner and Naidu, 1997; Faulkner, 2006; see also further in this section (Soil chemistry)).

Impermeable soil layer

Decreasing water permeability in the subsoil is an important factor for piping as pipes are often reported to develop at significant subsurface textural discontinuities in so-called 'duplex' soils or texture-contrast soils (e.g. Rooyani, 1985; López Bermúdez and Romero Díaz, 1989; Fitzpatrick et al., 1995). Soil horizons with slightly differing clay content will experience differential swelling and shrinkage (Imeson and Kwaad, 1980). This differential swelling causes stresses and creates macropores, hence focusing throughflow and pipe enlargement in particular horizons (Faulkner, 2006). Additionally, the occurrence of a highly permeable stratum underlain by impermeable strata is often reported as a requirement for piping (e.g. Parker and Jenne, 1967; Bryan and Yair, 1982; Farifteh and Soeters, 1999). Fletcher et al. (1954) stated that for piping to occur, a surface infiltration capacity greater than the subsoil permeability is needed, unless rodents or ploughing break the less permeable surface.

Macroporosity

Certain topographical settings promote the growth of macropores into pipes, i.e. an infiltrating surface, convergent flow paths to a lower outlet and a convex morphology in order to maintain positive hydraulic gradients within horizontal sections of a pipe network (Faulkner, 2006). Because the flow converges on the macropores under saturated conditions (pathway of least resistance to flow), the hydraulic gradient in the soil matrix near the entry point to the macropore can be quite large. In this way a continuous open path can be created, and thereby the formation of a continuous macropore or a soil pipe (Nieber et al., 2006). Also animal holes and burrows provide paths through heavier textured surface and subsoils to underlying strata of sand or gravel or extend laterally to adjacent streambeds or gullies (Carroll, 1949). Botschek et al. (2002a) pointed out that animal burrows were the most effective preferential flow paths in loess-derived soils in Germany, providing the necessary water supply for subsurface erosion.

Soil chemistry

The geochemical properties play an important role for piping in dispersive materials (Sumner and Naidu, 1997), but less in collapsible soils (see section 1.2.3.1). Dispersion is a physico-chemical process affecting certain clays with a 2:1 arrangement (e.g. smectite) in presence of monovalent cations (e.g. sodium; e.g. Sumner, 1992; Faulkner, 2006). The monovalent cations occupying exchange sites on the layers of the particular platelets, cause clay platelets to deflocculate (e.g. Sumner, 1992), because the bonds that initially existed between clays and other larger particles no longer exist (Faulkner, 2006). Consequently, flowing water can drag along the soil particles and pipes are formed. Evaluation of the soil water solution can be used for the assessment of the dispersive character of clayey material (e.g. Rengasamy et al., 1984), for example by means of a sodium adsorption ratio (SAR)/EC threshold plot (e.g. Faulkner et al., 2000). Farifteh and Soeters (1999) included soil material characteristics such as high exchangeable sodium percentage (>12%) and a high pH in their list of factors explaining the development of pipes in semiarid badlands. They studied clay-rich material, however, the influence of sodium is limited in other environments. Although sodium may contribute to the severity of piping in certain environments, it is not necessary for the occurrence of piping (Fletcher et al., 1945).

Human activity and land use change

Piping is observed under a variety of land covers and land uses from forest (Uchida et al., 1999; McIntosh and Laffan, 2005), over heath moorland or enclosed grassland (Jones et al., 1997), pasture (Botschek et al., 2002a; 2002b), agricultural land (Newman and Phillips, 1957; Floyd, 1974), abandoned agricultural terraces (Romero Díaz et al., 2007b) to badlands (Bryan and Harvey, 1985). Human activity has been blamed for the development of piping erosion in many parts of the world. According to Jones (1981), the problematic human activities can be divided into two categories: those which affect soil stability and those which affect the local water balance. The most commonly cited elements of human interference have been clearing land for agriculture and overgrazing, but also irrigation and construction works (Jones, 1981). Reduced protection of the soil by vegetation loss and livestock trampling leads to irregular infiltration, which favours piping erosion (Downes, 1946; Parker, 1963; Bryan and Jones, 1997). In peat in the UK, Jones and Cottrell (2007) observed a marked reduction in the number and size of pipes after afforestation. Compaction and pan formation due to agriculture encourage lateral movement of soil water, which can also enhance piping erosion (Conacher and Dalrymple, 1977). Activities that reshape the slope morphology (such as land terracing, road and field banks construction) will reduce soil bulk density and increase hydraulic gradients, increasing the chance for pipes to develop. When artificial structures such as terraces are abandoned or poorly-maintained, piping is usually enhanced (e.g. Kerényi, 1994; Romero Díaz et al., 2007a). Under certain conditions, over-irrigation can lead to soil salinization and/or sodification, thereby facilitating pipe formation (Garcia-Ruíz and Lasanta, 1995; Garcia-Ruiz et al., 1997). In blanket peats of the UK, land management (moorland gripping, surface drainage) was reported to be the most important control on hillslope pipe frequency (Holden, 2005). Artificially drained blanket peat catchments had a significantly greater soil pipe density than intact catchments (Holden, 2006).

1.2.3. Geographical distribution of piping

Piping is far more widespread than has often been assumed, forming in virtually all climates, in organic and mineral soils, on undisturbed and agricultural land and in certain unconsolidated sediments and bedrock (Jones, 1981; Dunne, 1990; Bryan and Jones, 1997). Soil pipes have been reported in a wide range of environments on every continent except Antarctica, from the tropical rain forest (Elsenbeer and Lack, 1996; Putty and Prasad, 2000) to periglacial regions with permafrost (Gibson et al., 1993; Quinton and Marsh, 1998; Carey and Woo, 2000; 2002). Piping appears to be of greatest geomorphological and hydrological significance in three environments: in organic soils on humid uplands, in badland areas in arid and semiarid environments, and in degraded semiarid rangelands (Bryan and Jones, 1997). Piping in Histosols and Gleysols seems to require a humid temperate climate. In a literature review, Jones (1994) found that 60% of the studied sites with piping occurred in humid regions (Fig. 1.2). On the other hand, dispersive-type pipes occur in a Mediterranean or semiarid context. In a wetter climate, sodium is lost so rapidly from the materials by leaching that the dispersive role on the clay complex does not persist (Churchman and Weissman, 1995; Faulkner, 2006). Also, in humid climates, the organic matter remains a structuring agent within the topsoil. In drier climates, clay is frequently the only structuring agent, so its dispersion has a dramatic impact (Faulkner, 2006). Both a reasonable water supply and some desiccation effects are needed, which gives peaks in the occurrence of piping in the semiarid and temperate marine environments (Bryan and Jones, 1997).

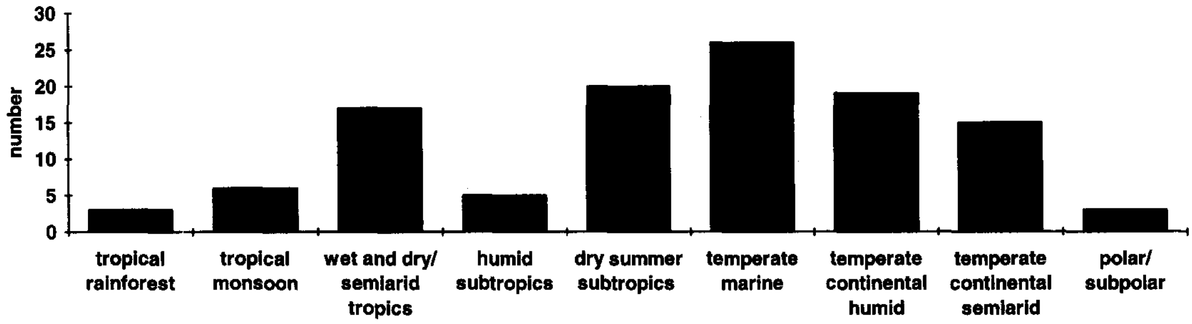


Fig. 1.2. Published observations of piping according to Jones (1994).

1.2.3.1. Different types of piping erosion in Europe

Three piping-prone contexts can be distinguished in Europe (Faulkner, 2006): (i) the organic peats (Histosol) and Gleysols in upland areas of Northern Europe, (ii) the dispersive sodic marls (Xerosols, Chromic Luvisols, Sodic Vertisols (Chromic), Solonetz) of Southern Europe, and (iii) the collapsible loess-derived soils (Luvisols) of the central European loess belt. Fig. 1.3 shows the distribution of these three piping-prone soil groups with indication of the sites where piping was observed (Table 1.1).

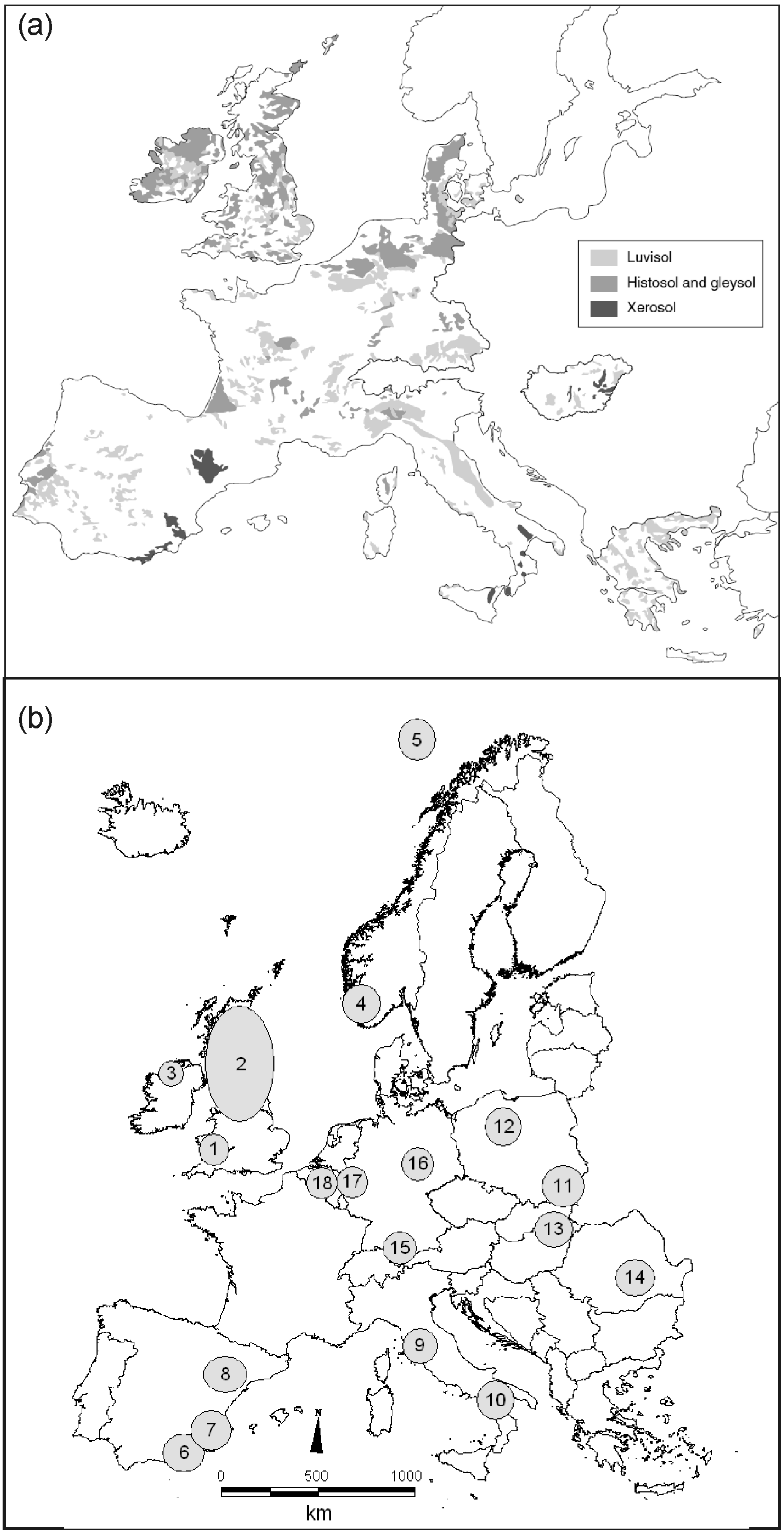


Fig. 1.3. (a) Distribution of the three major piping-prone materials in Europe according to Faulkner (2006) and (b) indication of the areas where piping was studied. The literature corresponding to each number is presented in Table 1.1.

Table 1.1. Observed piping in Europe corresponding to Fig. 1.3 b.

N°	Country	Region	References
1	UK	Wales	(e.g. Wilson and Smart, 1984; Jones and Crane, 1984; Jones, 1997b)
2	UK	Upland Britain	(e.g. Jones, 2004a; Holden, 2005)
3	Ireland	Cuilcagh Mountain	(Gunn, 2000)
4	Norway	Lake Skjervatjern	(Norrström and Jacks, 1996)
5	Norway	Spitzbergen	(Czeppe, 1965)
6	Spain	Almeria	(Harvey, 1982; López Bermúdez and Romero Díaz, 1989; Faulkner et al., 2003; Faulkner et al., 2004; Faulkner et al., 2008)
7	Spain	Murcia, Alicante	(Harvey, 1982; López Bermúdez and Romero Díaz, 1989; Romero Díaz et al., 2007b)
8	Spain	Ebro valley	(Benito et al., 1993; Garcia-Ruíz and Lasanta, 1995; Gutierrez et al., 1997; Echeverría et al., 2007)
9	Italy	Biancana badlands	(Torri et al., 1994; Torri and Bryan, 1997)
10	Italy	Basilicata	(Farifteh and Soeters, 1999; Piccarreta et al., 2006)
11	Poland	South-east	(Malicki, 1935; Czeppe, 1960; Galarowski, 1976; Rodzik et al., 2009)
12	Poland	Bukowiec	(Starkel 1960 in Galarowski 1976)
13	Hungary	Tokaj	(Kerényi, 1994)
14	Romania	Sub-Carpathians	(Balteanu, 1986)
15	Germany	South-west Bayern	(Scholz and Strohmenger, 1999)
16	Germany	Harzvorland	(Hardenbicker, 1998)
17	Germany	Area around Bonn	(Botschek et al., 2000; Botschek, 2002; Botschek et al., 2002a)
18	Belgium	Central Belgium and Geul valley	(Gullentops, 1952; Govers, 1987; Poesen, 1989; Vanderputten, 2006)

Piping in Histosols and Gleysols of upland rural areas in Northern Europe

Jones et al. (1997) found that 70% of piping in the United Kingdom (UK) was located on the Histosols of upland rural areas. These soils are mostly peats and organic soils with high winter rainfall acceptance potential, a capacity to shrink and crack (Coquet, 1998) and distinctive discontinuities in subsurface permeability (Holden et al., 2002; Holden and Burt, 2002). Piping in peatlands was extensively studied in the UK, but also reported in Scandinavia and Ireland (e.g. Jones, 1981; Norrstrom and Jacks, 1996; Jones et al., 1997; Holden, 2005). The pipes are important hydrological and geomorphological agents, resulting in significant sediment and carbon loss (Holden et al., 2002; Holden, 2006)

Piping in dispersive materials in Southern Europe

The second context for piping in Europe is observed in the sodic and dispersive marine-sourced marl sediment in semiarid or Mediterranean climates of several central and Southern European sedimentary basins (Faulkner, 2006). Piping often occurs in soils containing more than 30-44% of clays with the 2:1 arrangement, which can both swell and shrink, causing surface polygonal cracking (Imeson, 1986). There is often hysteresis whereby the amount of swelling during the wetting is less than preceding shrinkage, leaving cracks open which enhances infiltration rates (Faulkner, 1990). Furthermore, the geochemistry of the material can be critical in the case of dispersive soils because it affects both the hydrological and erosion response of the soil (e.g. Mualem and Assouline, 1992; Sumner, 1992; Levy, 2000; Faulkner et al., 2000; see also section 1.2.2. Soil chemistry).

Piping in collapsible or poorly structured soils of the European loess belt

In this study, the focus is on pipe development in collapsible or poorly-structured soils formed in loess material as observed in Poland (e.g. Malicki, 1935; Czeppe, 1960; Malinowski, 1963), Germany (Hardenbicker, 1998; Botschek et al., 2002b) , Hungary (Kerényi, 1994) and Belgium (Gullentops, 1952; Govers, 1987; Poesen, 1989). These collapsible soils are characterised by very high silt percentages and low clay content, which lead to a low aggregate stability and a high susceptibiliy to erosion (e.g. Poesen, 1993). This situation is further exacerbated by low organic matter content. After saturation by water, rearrangement of particles results in a loss of volume and reduced shear strength, which makes the material subject to subsidence and sliding (e.g. Pye, 1984; Derbyshire et al., 1995). Cracks can be produced in this change of state and act as macropores which enhance infiltration. These or other pre-existing macropores can become preferential flow paths and, because of the very erodible poorly structured nature of the materials, can lead to pipe development (Faulkner, 2006). The positive feedback mechanism by which subsurface erosion enlarges pores, which consequently act as improved drains, ensures a good (and increasing) hydraulic gradient as pipe erosion proceeds. Unlike the dispersive soils in the Mediterranean, there is no relationship between the chemical soil properties and the susceptibility to piping for loess-derived soils in Germany (Botschek et al., 2002b). Little is known about the factors controlling piping in this environment.

1.3. OBJECTIVES AND OUTLINE OF THE THESIS

The literature review indicates that the general requirements for piping are well documented. In loess-derived soils of temperate humid regions, however, there is still a lack in the understanding of the significance of piping in terms of soil loss and hydrological functioning. Furthermore, information about the key factors –and their relative importance– controlling piping occurrence is limited for this environment. Knowledge of these factors is needed for defining zones with a high susceptibility to pipe collapse. So far, attempts for modelling pipe collapse occurrences were physically-based. However, these models require detailed geotechnical and hydrological data which is generally not available on a regional scale. Hence, it should be investigated whether it is possible to model susceptibility to pipe collapse with a statistical model. Also detection of pipes that did not (yet) collapse is still a challenge.

Therefore, the overall objective of this dissertation is to better understand the spatial patterns of collapsed pipes and the process of piping erosion in the Flemish Ardennes. More specific objectives are:

- (i) to evaluate the effectiveness/performance of techniques for detecting locations and susceptibility of piping;
- (ii) to estimate the significance of piping in terms of subsurface soil loss
- (iii) to determine factors controlling the spatial patterns of piping in the study area and the relative importance of these factors, which will allow the development of statistical modelling procedures and the creation of a susceptibility map for pipe collapse in the study area; and
- (iv) to study the hydrological functioning of pipes and to determine the origin of subsurface runoff in the pipes (groundwater and/or rainfall)

The thesis is conceived as a compilation of four scientific papers as a first author (Chapter 3, 4, 5 and 7), one as co-author (Chapter 2) and two additional chapters with research results (Chapter 6 and 8). Each paper is presented as one chapter in this thesis dealing with one of the above-mentioned objectives and, in principle, could be read individually. However, the different chapters are clearly linked to each other and attention is given to the logical order of the chapters throughout the thesis. Some overlap may occur in the various chapters, especially considering the database description. The main research questions along the thesis are given in Fig. 1.4.

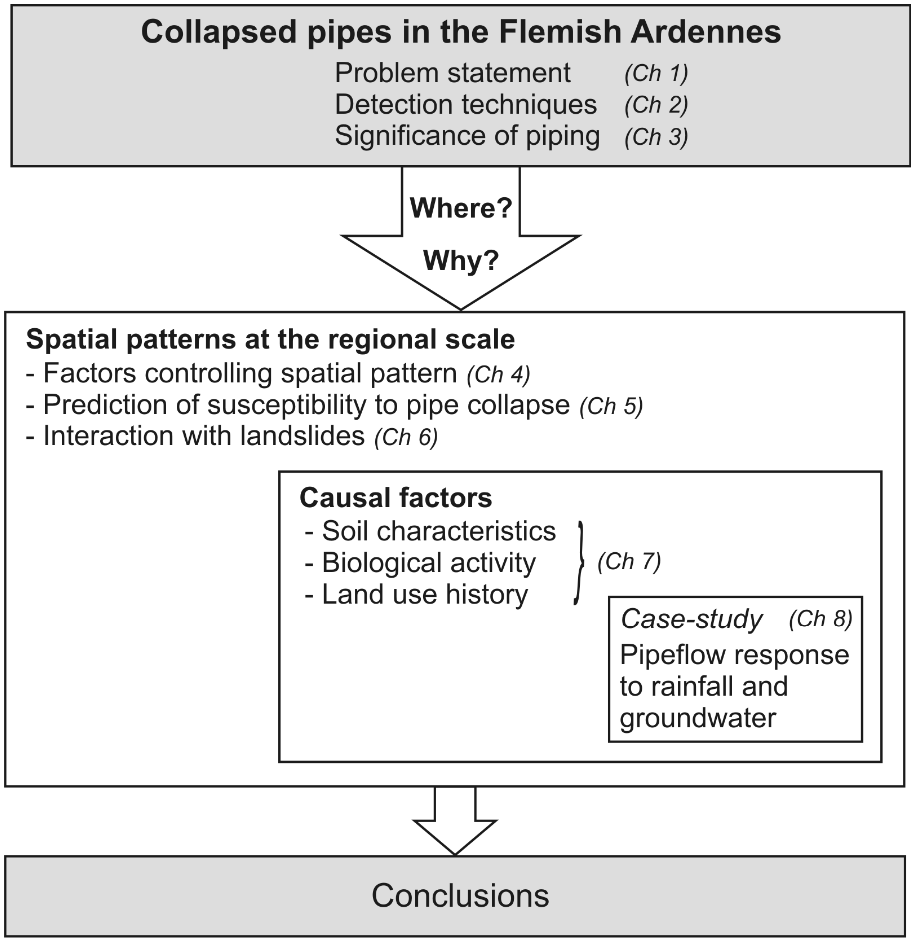


Fig. 1.4. Research questions and structure of the thesis.

The first three chapters form a broad introduction on the problems related to and the significance of piping erosion. Chapter 1 illustrates the need for more detailed investigations through an overview of the available literature and describes the study area. Chapter 2 discusses the evaluation of geophysical techniques for pipe detection and of the pinhole test, a laboratory test used for assessing piping susceptibility of different loess-derived soil horizons. From the detected collapsed pipes in the study area and their morphological characteristics, soil loss rates due to piping are estimated in Chapter 3 in order to evaluate the importance of piping erosion in the study area as well as in comparison with other environments.

The second part of this dissertation deals with the research on the spatial patterns of pipe collapse at the regional scale (i.e. 139 sites with 560 collapsed pipes in the study area). The factors controlling the spatial patterns of collapsed pipes are discussed in Chapter 4 by confronting the location of the collapsed pipes with maps depicting topography, lithology, soil types and land use. Based on these factors, two susceptibility maps are created using (1) logistic regression and (2) topographical thresholds derived from the slope-drainage area relation (Chapter 5). The spatial patterns of the collapsed pipes are further compared to the distribution of landslides in the same area to determine their interaction (Chapter 6).

After analysing the regional spatial patterns, we zoom into a representative sample of the sites to determine the local causal factors and gather insight in the process of piping. First, 12 sites with and without collapsed pipes were studied in greater detail to investigate the influence of different soil characteristics and of the biological activity on pipe development, as well as the effect of the land use history (Chapter 7). Secondly, some hydrological aspects of piping are discussed in Chapter 8. Therefore, rainfall, groundwater and pipeflow were monitored in one small catchment with piping to determine their interaction.

Finally, the research at all scales is brought together in Chapter 9, summarizing the conclusions and recommendations for further research.

1.4. STUDY AREA: THE FLEMISH ARDENNES

This process of piping is common in the Flemish Ardennes in Belgium (Fig. 1.5.) where it causes collapse of the topsoil and formation of discontinuous gullies. Therefore, this study focuses on an area of 236 km² consisting of the following five municipalities: Ronse, Kluisbergen, Maarkedal, Oudenaarde and Brakel (Fig. 1.6). It is a representative area for the steeper hillslope of the Flemish Ardennes, sufficiently large and containing sufficient collapsed pipes. A detailed description of the Flemish Ardennes is given by Van Den Eeckhaut (2006). The area has a maritime temperate humid climate with mild winters (‘Cbf’ according to the Köppen classification) and an average annual rainfall of ca. 800 mm well distributed over the year (792 mm for Oudenaarde; KMI, 2003). It is a hilly region with altitudes ranging from 10 m a.s.l. in the valley of the river Scheldt to 150 m a.s.l. on the Tertiary hills, located east of this river. The greater part of the area (99.5%) has slope gradients less than 20%. The topography is characterized by a systematic valley-asymmetry, as the slopes oriented south to northwest are steeper (Vanmaercke-Gottigny, 1995).

Fig. 1.5. Typical landscape of the Flemish Ardennes (Kluisbergen, October 2007).

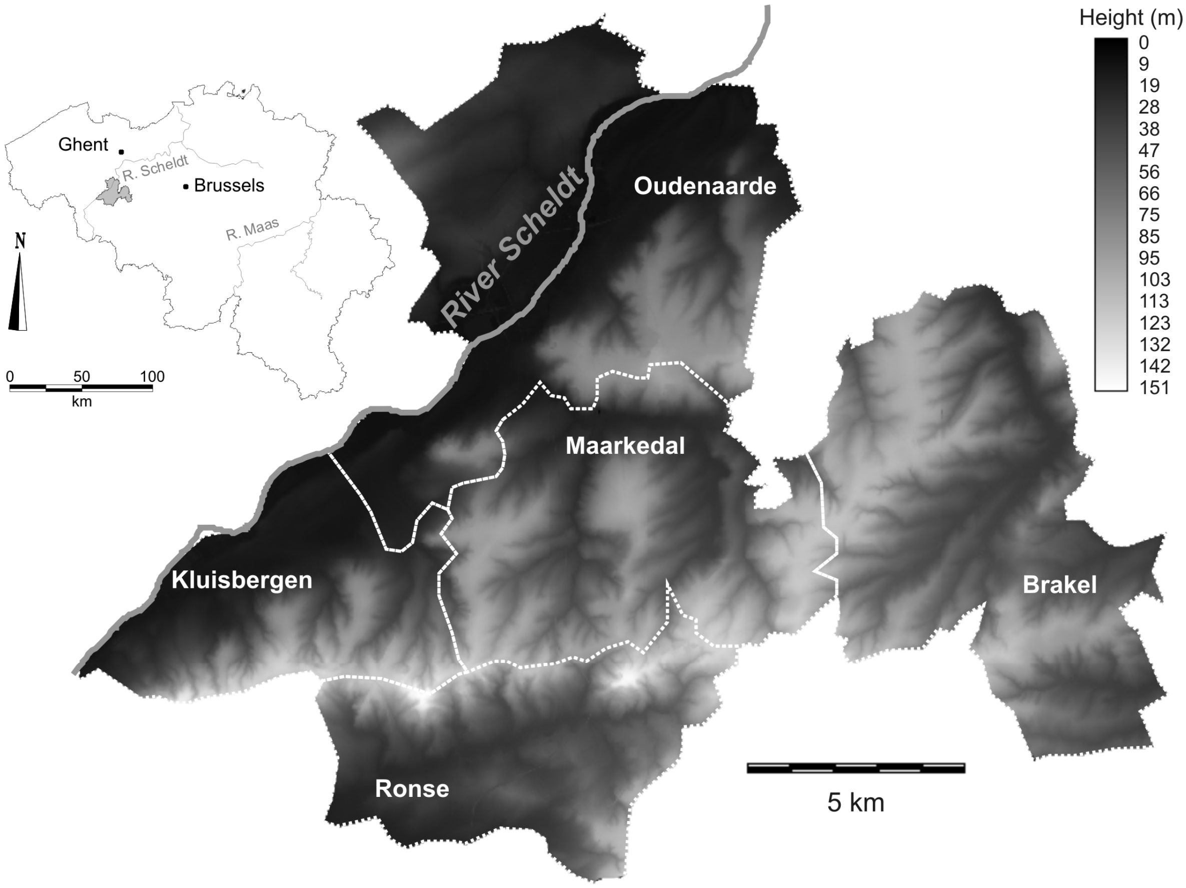


Fig. 1.6. Location of the study area in Belgium and topography of the study area (236 km²) with indication of the investigated municipalities (based on DEM of Flanders, 2004).

The lithology consists of loose Tertiary marine sediments which are overlain by Quaternary loess with varying thickness. The Tertiary lithology is an alternation of sands and less permeable smectite-rich clays in subhorizontal layers with a dip of less than 0.4% to the north-northeast (Jacobs et al., 1999a). A more detailed description of the lithological layers outcropping in the study area is given in Table 1.2. (Jacobs et al., 1999a, b). The old stratigraphic classification was used to allow comparison with available geological maps and literature. According to the new international stratigraphic chart of the International Commission of Stratigraphy (Oggs et al., 2008), the Eocene is a subdivision of the Paleogene period and Cenozoic era. The Kortrijk Formation outcrop covers about 67% of the whole study area. The Aalbeke Member of the Kortrijk Formation, a thin layer of homogenous clays, encircles the younger Formations of Tielt, Gent, Lede, Maldegem and Diest (Fig. 1.7).

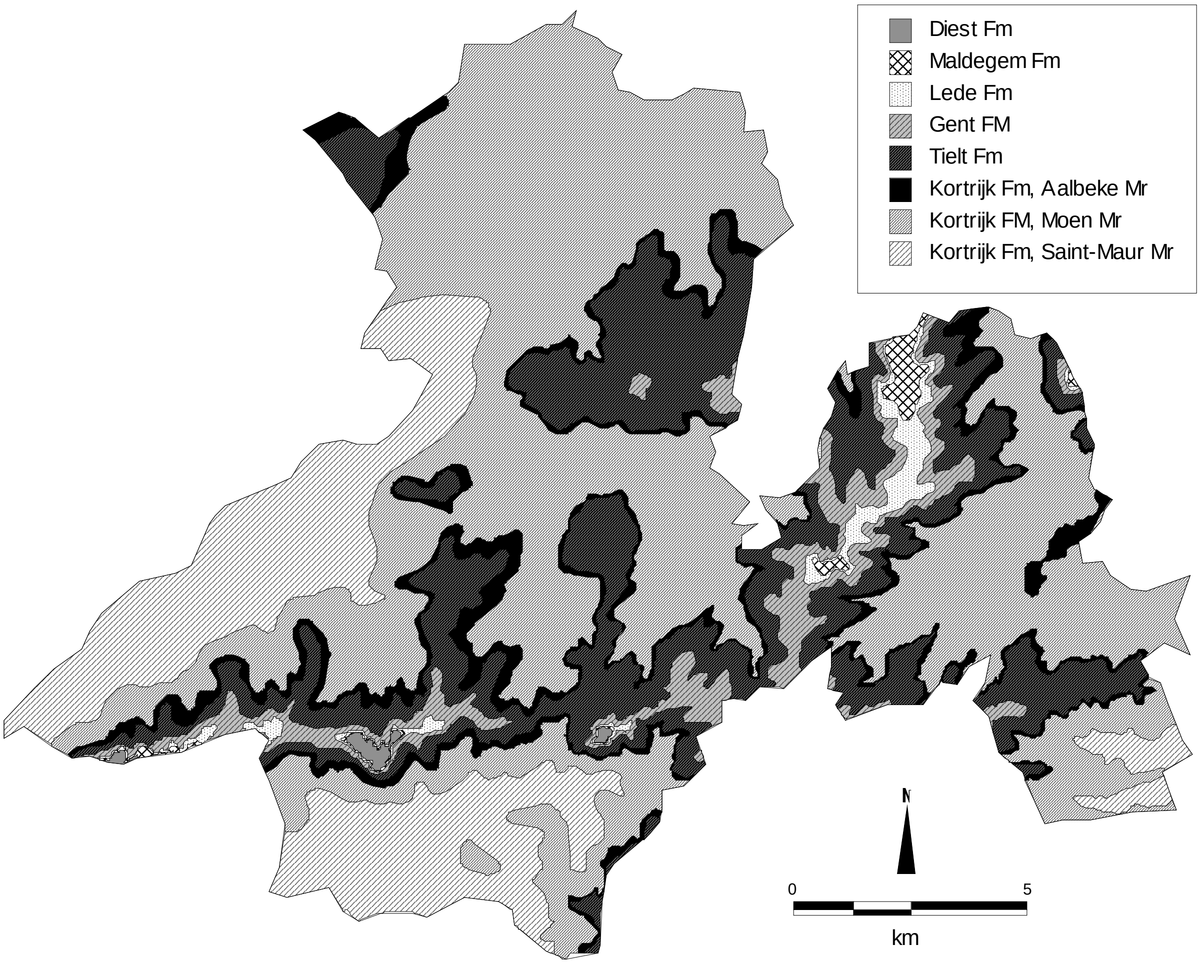


Fig. 1.7. Tertiary geology of the study area. See Table 1.2. for information on the lithology of the different formations and members (based on AGIV, 2001a). Fm = Formation, Mr = Member.

The correspondence of the lithological and the topographical contour lines results from differential erosion of the subhorizontal lithological layers during the Late Tertiary and Early Quaternary (Van Den Eeckhaut, 2006). Eolian sediments (loess) have covered the Tertiary topography during the cold periods of the Pleistocene (I.W.O.N.L., 1987). Most hillslopes in the study area are covered by loess, deposited by north-eastern winds (Goossens, 1988; Goossens, 1997). The area of the Flemish Ardennes is situated in the Belgian loess belt (ca. 9 000 km², 40 to 80 km wide and 250 km long zone), which forms part of the larger European loess belt extending from northern France to Ukraine and Russia. From north to south the sand fraction decreases in favour of the silt fraction (I.W.O.N.L., 1987).

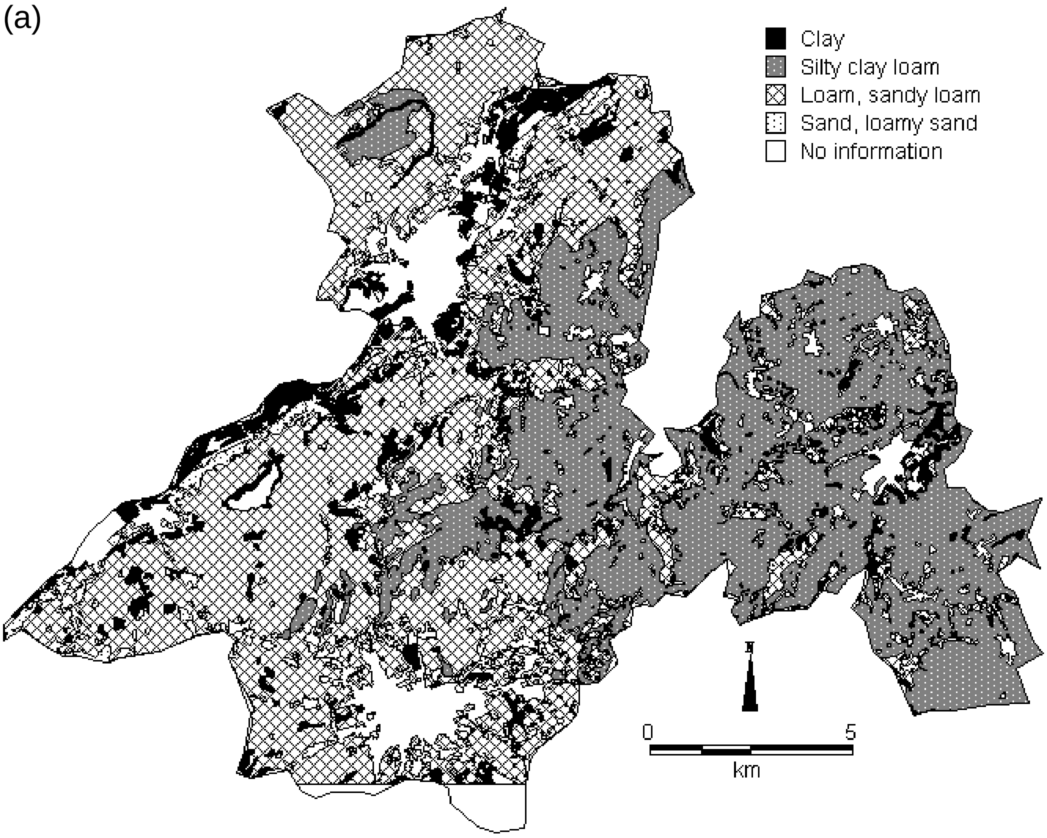
Weathering of the loess resulted in loamy soils (i.e. Luvisols and Albeluvisols). Fig. 1.8 shows the distribution of soil texture, soil drainage class and soil profile development derived from the Belgian soil map (AGIV, 2001b). Wet soils correspond to alluvial and colluvial sediments, but also to soils where a Tertiary clayey substrate is found within the first 120 cm. The presence of such clay layers hampers the vertical infiltration of the water (Closson et al., 1999) and often results in the formation of a perched water table. Due to the alternation of less-permeable clays and more permeable sands, perched water tables are a common feature in the Flemish Ardennes. Where the topography intersects a perched water table, springs occur. Many springs and a high drainage density (1.46 km km^{-2}) characterize the hydrology of the region.

Table 1.2. Geological layers in the study area (after Jacobs et al., 1999 a, b)

	Chrono-Stratigraphy (Period, mya)	Formation (Fm)	Member (Mr)	Lithology	Average thickness (m)
TERTIARY	Pliocene (5.4-1.77)	NP	NP	NP	NP
	Miocene (23.8-5.4)	Diest (Di)		Glauconitic, oxidized sand	2 to 3
	Oligocene (33.6-23.8)	NP	NP	NP	NP
	Eocene (54.8-33.6)	Maldegem (Ma)		Homogene blue clay and glauconitic sandy clay	2 to 3
		Lede (Ld)		Sand with three lithified sand layers rich in fossils	5
		Gent (Ge)	Vlierzele (GeVl)	Glauconitic sand with lithified sand layers and clay lenses	5
			Merelbeke (GeMe)	Dark clay with sand lenses	5
		Tielt (Tt)		Micaceous and glauconitic clayey sand, alternating with many lithified sand layers and clay layers	20 to 30
		Kortrijk (Ko)	Aalbeke (KoAa)	Homogeneous blue massive clay	10
			Moen (KoMo)	Clayey coarse silt to fine sand with clay layers	45
			Saint-Maur (KoSm)	Silty clay	27
			Mont-Héribu (KoMh)	Glauconitic clayey sand, sandy or silty clay	NP
	Paleocene (65.0-54.8)	NP	NP	NP	NP

NP: not present in study area

(a)



(b)

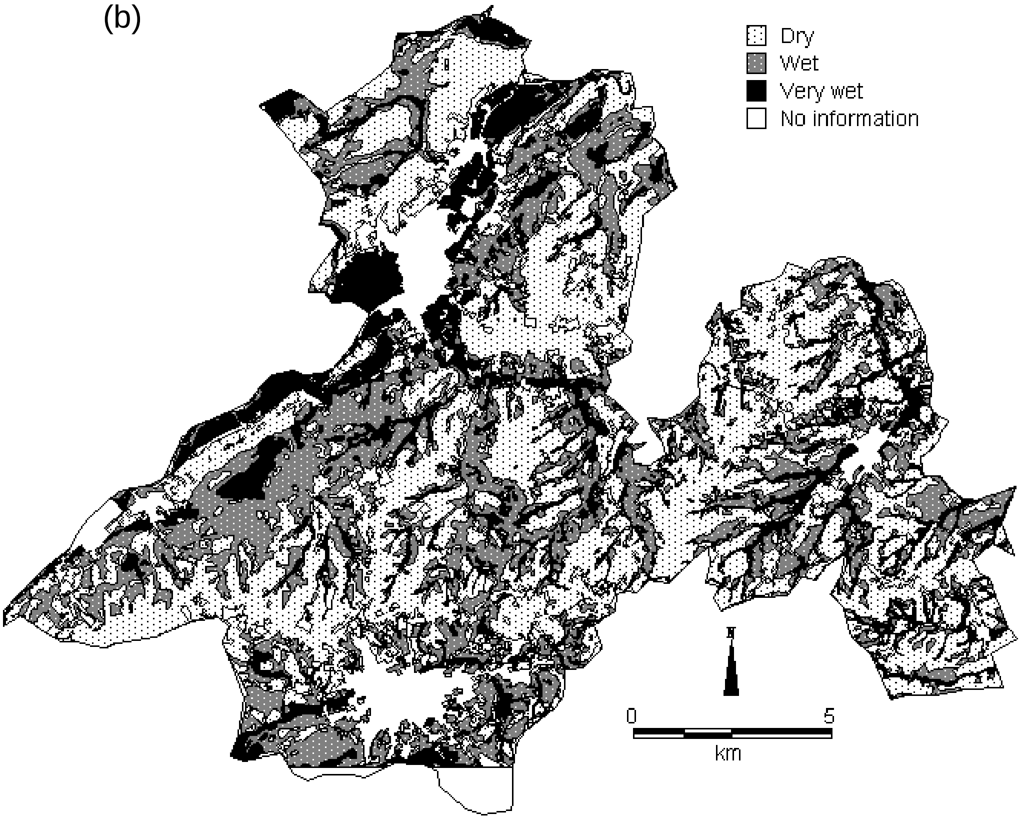
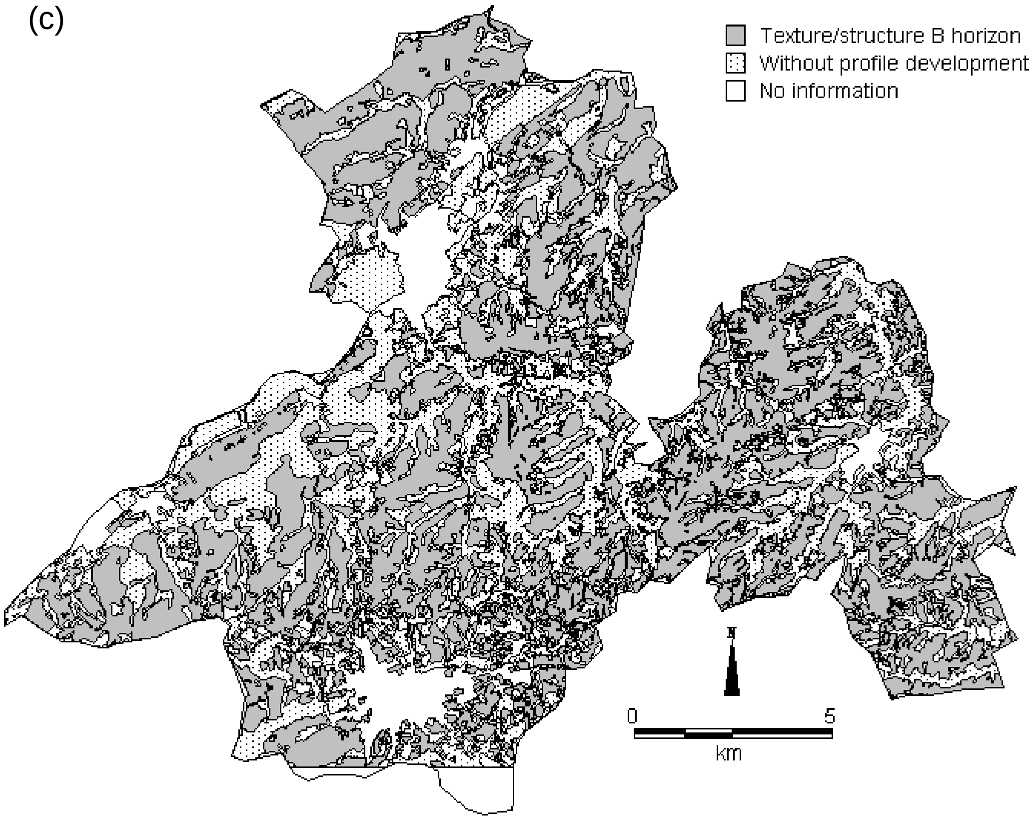


Fig. 1.8. Distribution of soil characteristics in the study area (AGIV, 2001b), converted from the Belgian soil taxonomy, with (a) soil texture, (b) soil drainage and (c) soil profile development.

(c)



Continued Fig. 1.8. Distribution of soil characteristics in the study area (AGIV, 2001b), converted from the Belgian soil taxonomy, with (a) soil texture, (b) soil drainage and (c) soil profile development.

Land use is strongly determined by lithology, soil type and topography. Cropland is located on the loess-covered plateaus of the lower hills. Pastures dominate the hillslopes mainly because of their steepness and/or wet soil conditions, sometimes in combination with a shallow loess cover, which makes these hillslopes less suitable for cropland. The highest loess-free Tertiary hills and the steepest hillslopes are typically covered by forest.

Chapter 2

Evaluation of techniques for piping detection and piping susceptibility

This chapter reports on the techniques tested (i) for detection of piping in the field and (ii) for the assessment of piping susceptibility of different soil horizons in the lab. First, an evaluation is made of geophysical methods for detecting and mapping uncollapsed pipes which are not yet collapsed in the study area through a collaboration with the Forschungszentrum Jülich (Germany)*. In the second part of this chapter, the pinhole test is evaluated for quantitative assessment of the piping susceptibility of the horizons of a typical loess-derived Luvisol.

2.1. DETECTION OF SOIL PIPING USING GEOPHYSICAL METHODS: A CASE STUDY IN BRAKEL

2.1.1. Introduction

The presence of piping erosion is mostly recognized by linear depressions and collapses expressed at the soil surface, but it is difficult to assess the connectivity of the soil pipes from such observations. In favourable conditions, vegetation patterns can be used to establish linkages in the pipe network (e.g. Wilson and Smart, 1984; Jones, 2004a). However, the most direct and reliable way to assess the connectivity of soil pipes is the use of dye tracing (e.g. Jones and Crane, 1984) in combination with excavation of profile pits. Clearly, an improved understanding on the formation and importance of soil piping could be obtained if subsurface networks of pipes could be measured directly, instead of inferred from the surface expressions or from destructive and time-consuming methods such as excavation of profile pits.

Near-surface geophysical methods have the potential to address this need, since they have already been widely applied to detect cavities and pipes in geological and civil engineering applications (e.g. Maillol et al., 1999; Oh and Sun, 2008). These

* Contribution of different researchers:
Field measurements: Verachtert, E., Huisman, J.A., André, F., Busch, S., Moghadas, D., Rings, J.; Data processing: Dahlke, C., Huisman, J.A., André, F., Busch, S., Rings, J., van der Kruk, J.; Interpretation, writing, compiling: Verachtert, E., Huisman, J.A. and Dahlke, C.

studies investigated geological and pedological features, such as cavities and soil pipes, and mostly focussed on karst areas and the detection of dolines and sinkholes. For example, Electrical Resistivity Tomography (ERT) was reported to be an ideal tool to support the detection of sinkholes and subsurface cavities in dolomitic areas (van Schoor, 2002). Ahmed and Carpenter (2003) used ERT and ElectroMagnetic Induction (EMI) surveys to investigate the connections between soil pipes and hydraulically active bedrock fractures in karst terrain. Based on a conceptual model of sinkhole development, Zhou et al. (2002) concluded that the dipole–dipole array was the most effective and less costly electrode configuration for mapping karst hazard areas with ERT. In Spain, the sequential application of magnetic, low-frequency Ground-Penetrating Radar (GPR) and microgravity techniques was successful in detecting underground cavities and dolines (Mochales et al., 2008). Several studies showed the high potential of GPR for locating buried pipes (e.g. Gamba and Belotti, 2003; Soldovieri et al., 2008; Pettinelli et al., 2009), such as utility pipelines or agricultural drainage pipes (e.g. Allred et al., 2004). Successful detection of natural soil pipes with GPR was already demonstrated for blanket peat in the UK (Holden et al., 2002; Holden, 2004). GPR similations of Vanderputten (2006) revealed that the minimal detectable diameter of a water-filled pipe would be 10 cm at 1 m depth.

In this part of the chapter, the use of geophysical detection methods is evaluated in a case study near Brakel (Belgium). The specific objective of the survey was to test the suitability of GPR, ERT and EMI methods to identify natural soil pipes in a small catchment characterized by loess-derived soils.

2.1.2. Materials and methods

2.1.2.1. Site description

In the study area in the Flemish Ardennes, a pasture with collapsed pipes visible at the surface was chosen as a representative study site. The site is located near Brakel (Fig. 2.1; 50.769°N 3.777°E). The slope gradient ra nges from 8 to 17% in the area of the collapsed pipes. The lithology of the site consists of clayey coarse silt to fine sand with clay layers (Formation of Kortrijk, Moen Member), overlain by homogeneous blue massive clays containing more than 50% clay (Aalbeke Member; Jacobs et al., 1999b; Van Den Eeckhaut, 2006) in the upslope part of the site (Tertiary geological map 1:50,000; AGIV, 2001a). The soil map (1:20,000; AGIV, 2001b) indicates silty clay loam soils with minor gleyic colour patterns and argic horizons (Aca, Belgian Soil Classification) and silty clay loam soils with gleyic colour patterns at shallow depth (50-80 cm; Adp) for the site, which correspond to Siltic Luvisols and Endogleyic Vermic Siltic Regosols in the World Reference Base soil taxonomy (IUSS Working Group WRB, 2007). Soil textural analysis of samples taken at the study site (depth of 10, 35, 65 cm) showed a silt loam texture with silt fractions (2-63 μm) ranging from 66 to 77%. The hydrology of the region is characterized by many springs and a high drainage density (1.46 km km^{-2}). At the study site, there is a spring in the forest east of the pasture.

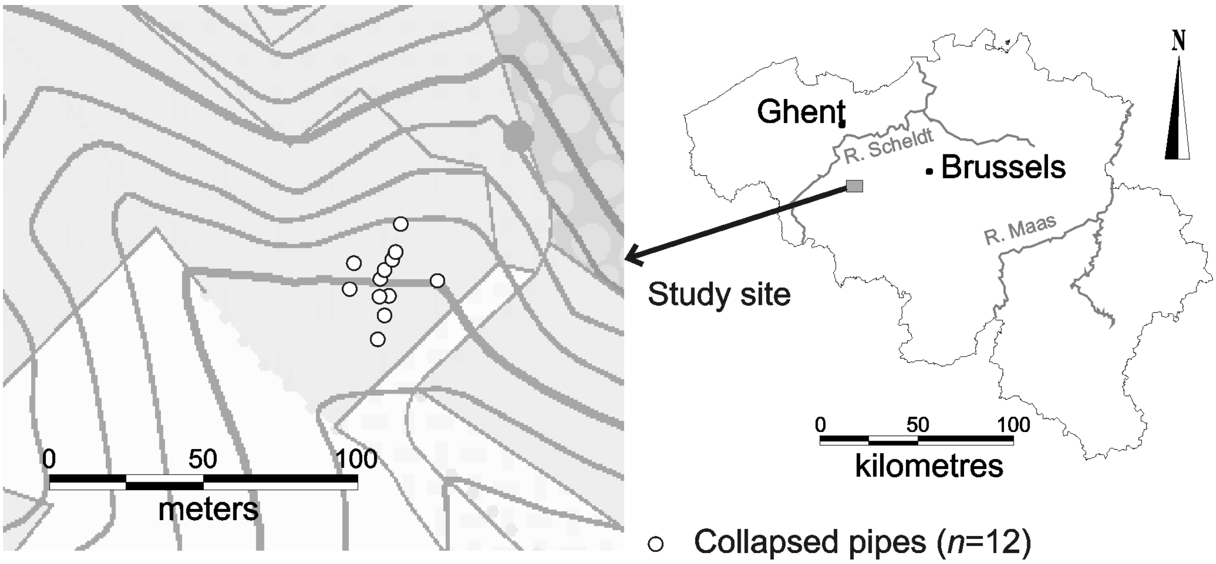


Fig. 2.1. Topographic map of the study site with indications of observed collapsed pipes (left) and location of the study site in Belgium (right).

2.1.2.2. Geophysical Measurements

Three different geophysical methods, ERT, GPR and EMI were tested to detect soil pipes of a soil tunnel system at the study site. Fig. 2.2 and Fig. 2.3 illustrate the study site and transects measured with the geophysical methods.

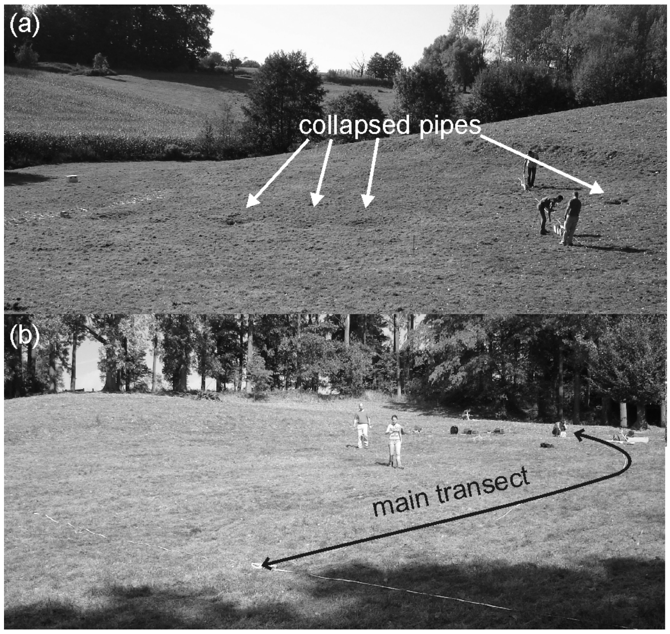


Fig. 2.2. Pictures of the study site with indication of (a) the collapsed pipes and (b) the main transect (T11).

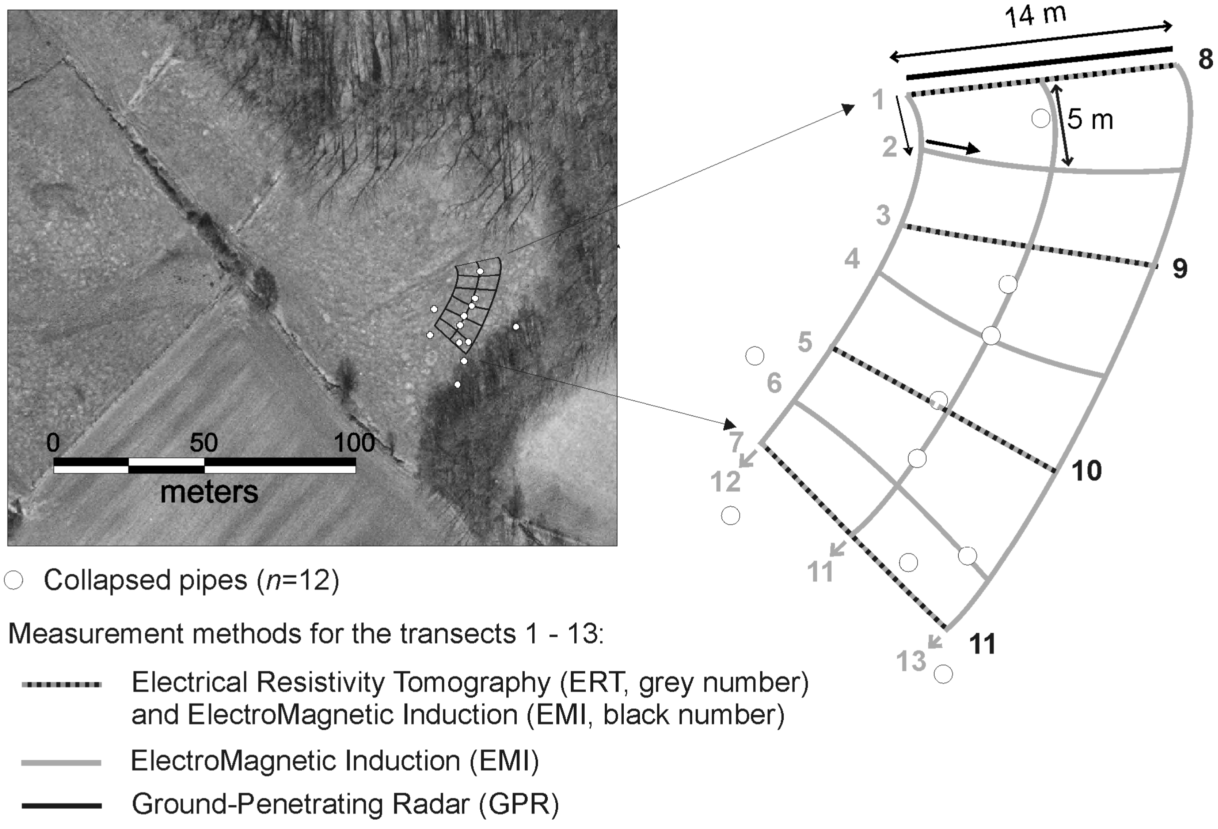


Fig. 2.3. Aerial orthophoto of the study site and overview of the transects measured with the geophysical methods

Electrical Resistivity Tomography (ERT)

ERT is commonly used to obtain images of the bulk electrical resistivity in the subsurface. In this study, 2D surveys were made along four transects (T1, T3, T5 and T7) at 10 m intervals perpendicular to the main transect and the line of partly collapsed soil pipes. Each ERT transect was 14.1 m long and consisted of 48 electrodes equally spaced with a separation of 0.30 m. In ERT, current is injected into the ground using two electrodes and the resulting potential difference is measured between two different potential electrodes. The arrangement of the four electrodes used for current injection and potential measurements is referred to as the electrode array. An ERT survey consists of many different combinations of current injection and potential measurements, typically using one type of electrode array. Two different electrode arrays were evaluated in this study: a multi-gradient and a dipole-dipole electrode array. For the multi-gradient electrode array, 2427 combinations of current injection and potential difference were measured and for the dipole-dipole electrode array, 911 such combinations were measured using an IRIS Syscal Pro ERT multi-channel measurement system. This system allows for faster measurements by taking up to 10 measurements at different pairs of potential electrodes at the same time. The measured apparent electrical resistivity data were converted into images of the electrical resistivity distribution in the subsurface by minimizing the absolute difference between measured and modelled apparent electrical resistivity in the RES2DINV software. The quality of the fit is reported as the root mean square error (RMSE) between measured and modelled apparent resisitivity normalized by the variance of the measured apparent electrical resistivity data (i.e. relative RMSE).

Ground-Penetrating Radar (GPR)

GPR emits electromagnetic waves into the soil using a transmitting antenna. The energy transmitted in the soil will partly be reflected when a contrast in soil dielectric permittivity is encountered (e.g. soil layers with different water content, soil pipe) and will be recorded by the receiver antenna as a function of time (e.g. Huisman et al., 2003). In this study, a bistatic GSSI TerraSIRch 3000 with a 200 MHz antenna was used to measure with a fixed antenna separation along transect 1 (see Figure 2.3). A time window of 80 ns was used to record reflected electromagnetic waves. This time window can be converted to depth when the propagation velocity of the electromagnetic waves is known. This velocity depends on the dielectric permittivity of the soil, and we assumed a velocity of 0.06 m ns^{-1}. This corresponds to a soil permittivity of 25 and a soil water content of ~0.4 m^3m^{-3} (Topp et al., 1980). Before interpretation, the raw GPR data were processed using the software ReflexW. In the common-offset GPR measurements made here, soil pipes are expected to show up as reflection hyperbola where the apex indicates the position of the soil pipe. This is because objects will be detected from different distances when the GPR device moves along the transect. When the antenna receives signals reflected from some distance, the time the wave needs for travelling to and from the object is longer than when the antenna is situated directly above the detected object. Therefore, a pipe will show up as a hyperbolic reflection (Holden et al., 2002).

Electromagnetic Induction (EMI)

The EMI technique measures the apparent soil electrical conductivity by inducing electrical currents in the soil using a source loop and measuring currents associated with the primary and secondary electromagnetic fields in a second receiving loop. Typical source-receiver orientations to measure apparent electrical conductivity are horizontal dipoles (i.e., vertical coplanar loops) and vertical dipoles (i.e., horizontal coplanar loops). These orientations have different depth and lateral sensitivity (McNeill, 1980). In this study, electromagnetic induction data were acquired using the Profiler EMP 400 (GSSI) using three different frequencies (5, 10 and 15 kHz) and both a vertical and horizontal coplanar loop orientation along all transects shown in Fig. 2.3. The Profiler EMP 400 was calibrated automatically following the procedure recommended by the manufacturer before starting the measurements.

2.1.3. Results and discussion

2.1.3.1. Electrical Resistivity Tomography

ERT measurements with the multi-gradient arrays were not successful in detecting soil pipes at the study site (Fig. 2.4a), although the relative RMSE of 2.6% indicates that the measured apparent electrical resistivity is well described. There are no conspicuously high electrical resistivity areas that could correspond to the presence of resistive air-filled soil pipes. Instead, general pedological structures were observed with a top soil with higher electrical resistivity (100 to 200 Ωm) overlying a second layer with lower resistivity values (50 to 60 Ωm). This contrast can be caused by differences in soil water content, clay content or soil porosity. Similar results were obtained for ERT measurements in the dipole-dipole electrode configuration (Fig. 2.4b). Here, the relative RMSE of 7.0% indicates a poorer fit to the data, which is related to the poorer signal-to-noise ratio typically observed for the dipole-dipole electrode configuration.

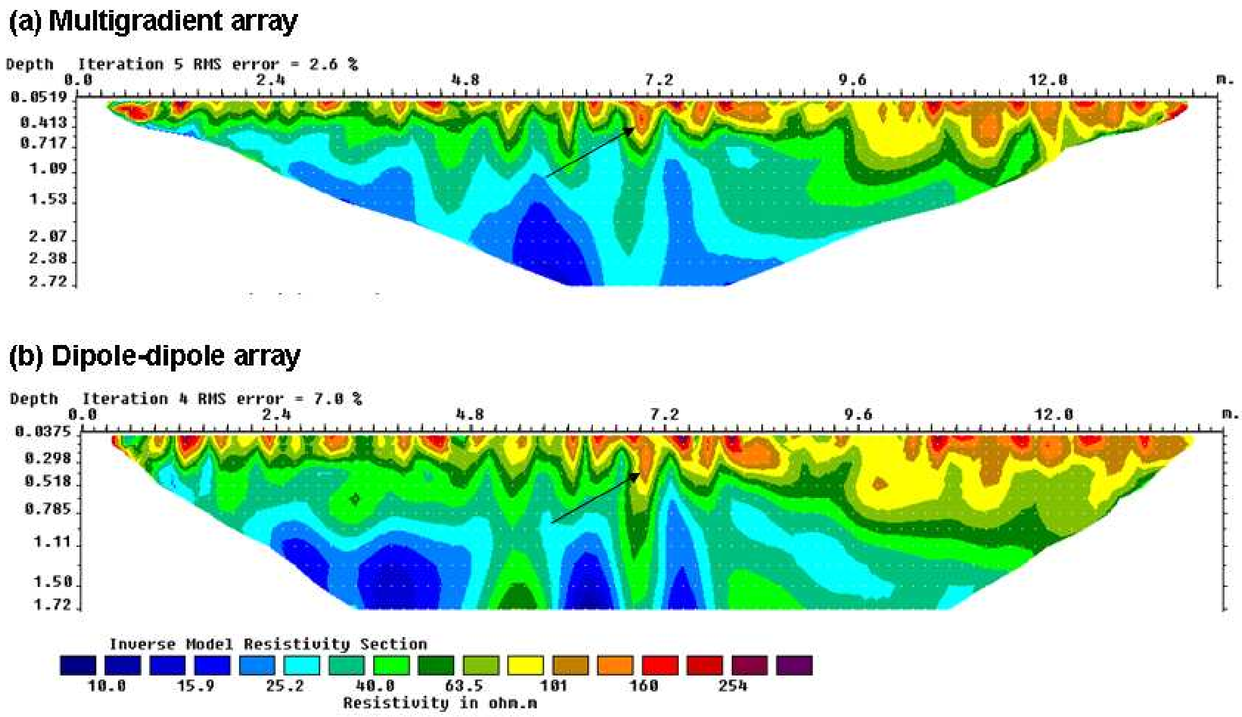


Fig. 2.4. Profiles of the electrical resistivity using (a) the multi-gradient array and (b) the dipole-dipole array for transect 1. Electrodes were placed every 0.30 m (larger ticks). The arrows indicate the location where the pipe is expected.

For a better understanding of the possibilities and limitations of detecting soil pipes with ERT in this soil type, Dahlke et al. (in prep) performed a forward modelling study using RES2DMOD to investigate different measurement strategies, pipe locations and pipe fillings (air, water). These simulations showed that even for soil pipes of 15 x 20 cm, the technical limitations associated with electrode spacing, ERT survey design, and current ERT interpretation methods limit the resolution and sensitivity such that these small-scale features can not reliably be identified. Other studies have shown that larger cavities and sinkholes in karst areas can be mapped with ERT (van Schoor, 2002; Ahmed and Carpenter, 2003; Park et al., 2009). Therefore, the potential of ERT for detecting larger pipe cavities, just before roof collapse, should be investigated. In addition, model simulations suggested that alternative interpretation methods that do not attempt to provide a smooth electrical resistivity distribution might be worth exploring.

2.1.3.2. Ground-Penetrating Radar

The raw common-offset GPR measurements measured along transect 1 are presented in Fig. 2.5. Without processing of GPR data, no reflection hyperbola that indicating the presence of a soil pipe was visible. Therefore, further data processing and analysis were required as illustrated in Fig. 2.6. The first step in processing is the amplification of the signal amplitude as a function of time (upper left of Fig. 2.6). The resulting data are now dominated by horizontal reflections. Next, two standard GPR data processing steps (i.e. DC-shift, dewow) were applied to remove spurious low-frequency components from the GPR data (step 1 and 2 on Fig. 2.6). In a final step (step 3), the average of all traces was removed (lower left of Fig. 2.6). After these processing steps, an anomaly indicated by the arrow can be seen that is located at the approximate position of the soil pipe. The GPR measurement suggests a relatively shallow depth of about 0.25 – 0.50 m.

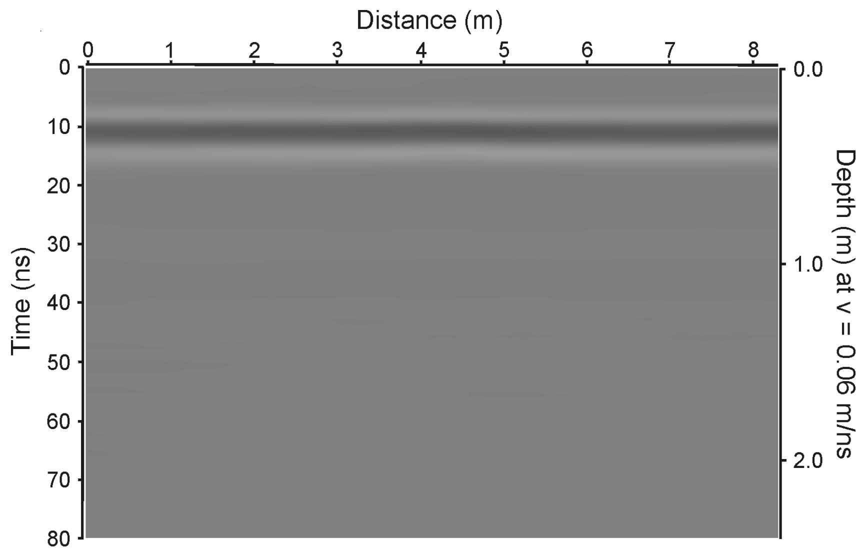


Fig. 2.5. Raw data of GPR measurement.

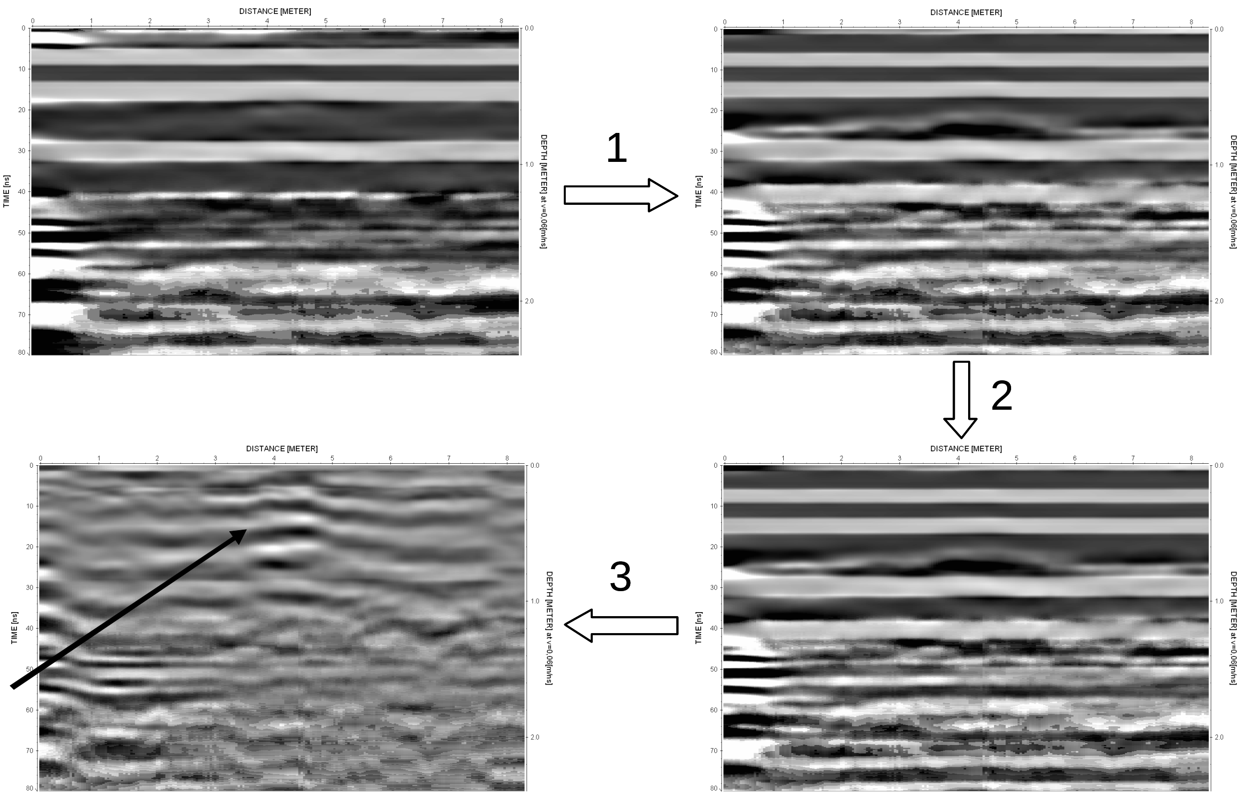


Fig. 2.6. Processed data of GPR measurement (axes identical to Fig. 2.5). Step 1, 2 and 3 are explained in section 2.1.3.2.

Nevertheless, it is stressed here that attenuation of GPR waves was strong, and, therefore, the penetration depth of electromagnetic waves was limited. Only after strong amplification, a signal possibly associated with a soil pipe was detected. Attenuation of GPR waves depends on many factors, including antenna frequency and soil conditions, such as soil moisture, clay content (Allred et al., 2004), salinity and the amount of iron oxides (Van Dam et al., 2002). Soil textural analysis showed silt contents between 66 to 77% at the study site. Huisman et al. (2001) already reported that such high silt contents resulted in strong attenuation and poor penetration of the GPR waves due to the low resistivity of these soils, which was determined to be 100 to 200 Ωm by ERT. Botschek et al. (2000) reported on the potential of GPR for soil pipe detection in loess-derived soils in Germany, and they were able to detect reflections for known pipes in the profile. However, the reflections were not clear in all cases and interpretation of the GPR image was not straightforward, very similar to the results reported here. It is emphasized here that GPR can be successful in the detection of soil pipes, as shown by Holden et al. (2002) for blanket peat in the UK using 100 and 200 MHz antenna. This is attributed to the higher resistivity of blanket peat, which improves signal penetration. Therefore, we conclude that GPR is not an appropriate tool for soil pipe characterization at this particular site. It is conceivable that GPR might be more successful when site conditions change (e.g. drier top soil) or at other sites prone to soil piping that have lower silt and clay content.

2.1.3.3. Electromagnetic Induction

The Profiler EMP 400 measurements in horizontal and vertical orientation are presented for transect 2 in Fig. 2.7. The EMI measurements did not indicate the presence of soil pipes when the apparent electrical conductivity was measured in the horizontal dipole orientation. However, the measurements made with a vertical dipole orientation indicate anomalous higher apparent conductivity values close to known soil pipe positions in most transects (Fig. 2.8). This can not be attributed to higher soil moisture in the vicinity of the active soil pipes, because such areas were not observed by ERT. Therefore, we speculate that the observed anomalies are related to a different sensitivity of the horizontal and vertical dipole orientations to small-scale resistive inclusions within the sampling volume of the EMI instrument, similarly as found for low-induction-number conditions (McNeill, 1980). Further research should focus on confirming this speculation and obtaining a quantitative understanding of the EMI response associated with the presence of soil pipes.

2.1.4. Conclusions

Standard measurement and interpretation strategies for ERT were not successful in detecting soil pipes. Currently, the sensitivity is not sufficient for detecting small pipes (< 20 cm diameter), but should be further investigated for larger pipe cavities of future collapses (cavities of > 50 cm diameter). Improvements in data interpretation might decrease the lower size limit of soil pipes detectable by ERT. The GPR method suffered from poor penetration of electromagnetic waves due to the low resistivity of the soil material. Only after strong signal amplification and data processing, a signal possibly associated with a soil pipe was detected. This is typical for soils with high silt content, which are unfortunately also the soils that are most prone to soil piping. If

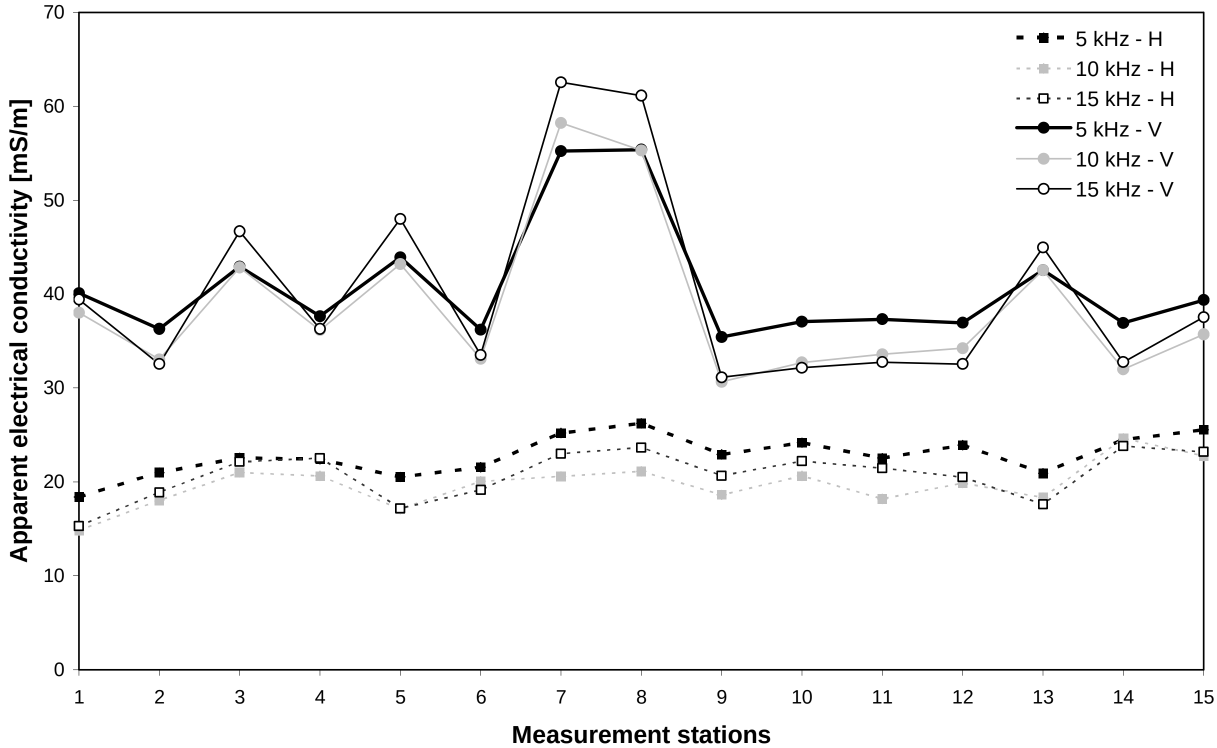


Fig. 2.7. Conductivity values along transect 2, measured with Profiler EMP 400 at different frequencies (5, 10 and 15 Hz) in both horizontal (H) and vertical (V) dipole modes.

sufficient energy penetrates, other studies have shown the high potential of this method. Therefore, additional field measurements at a range of sites with different pipe networks using multiple antenna frequencies are required for a better understanding of the effect of different field parameters on the ability of GPR to identify soil pipes. The EMI method indicated several anomalies close to known positions of the collapsed pipes when a vertical dipole orientation was used. It was speculated that this was related to a different sensitivity of the horizontal and vertical dipole orientations to small-scale resistive inclusions within the sampling volume of the EMI instrument. Therefore, a quantitative understanding of the EMI response associated with the presence of soil pipes is needed. In this respect, it will also be important to acquire denser EMI measurements in the field because of the expected complicated signatures in the apparent electrical conductivity associated with the presence of soil pipes.

The results in this study indicate that the geophysical methods evaluated here are not directly applicable for pipe detection in the loess-derived soils of the study area. However, a dedicated research program that tailors geophysical data acquisition and interpretation methods for the detection of soil pipes would substantially improve on the current state-of-the-art and would bring the in-situ detection of soil pipes a step closer. Experimental work in controlled conditions with simulated soil pipes of known dimensions could be useful.

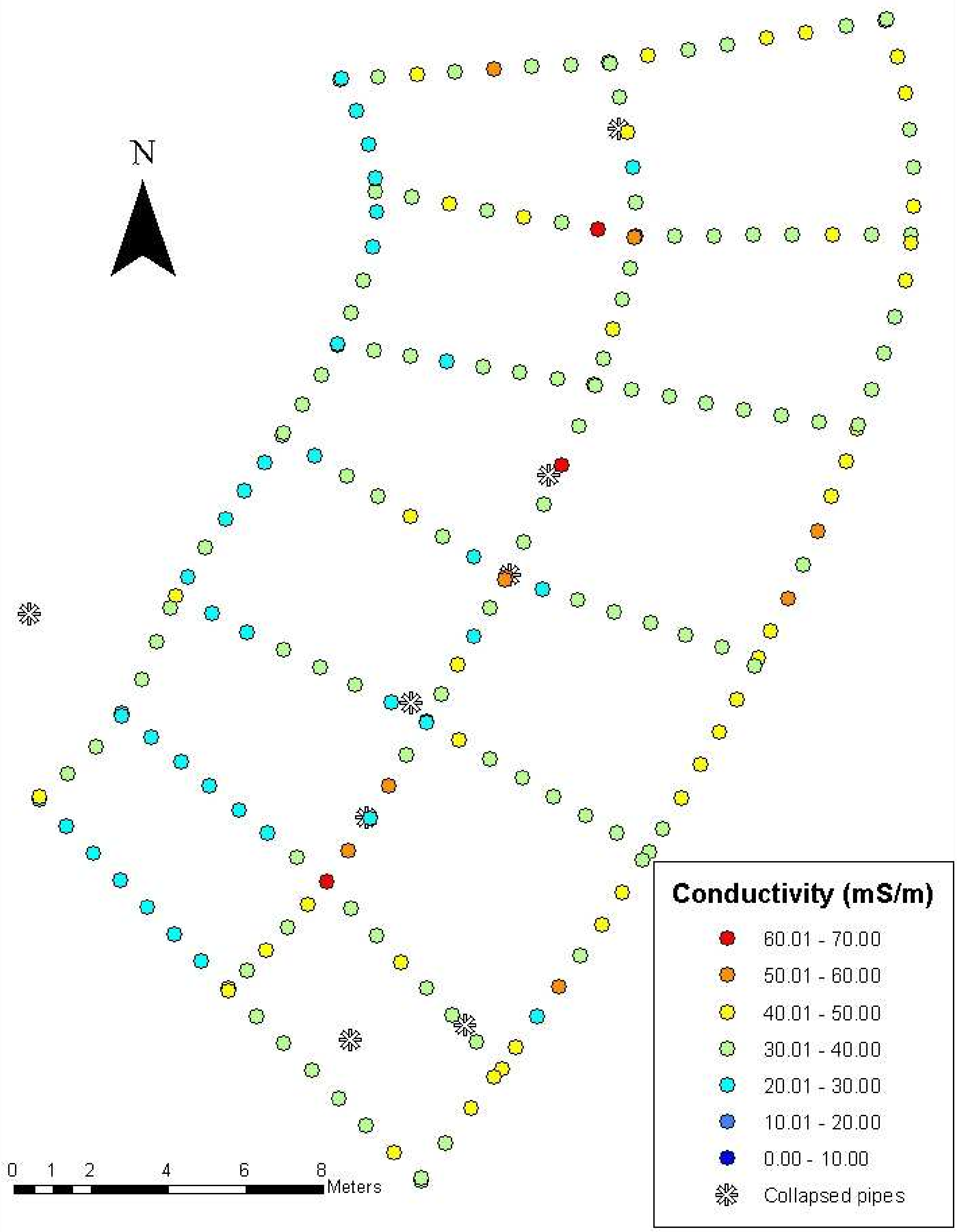


Fig. 2.8. Results of the vertical dipole EMI measurements with Profiler EMP 400 (15 kHz).

2.2. QUANTITATIVE ASSESSMENT OF THE PIPING EROSION SUSCEPTIBILITY OF LOESS-DERIVED SOIL HORIZONS USING THE PINHOLE TEST **

2.2.1. Introduction

In the loess belt, piping often typically occurs within earth banks, induced by Hortonian overland flow. When the runoff infiltrates into a macropore near an earth bank, the water will flow through a crack with a very steep gradient inducing intense subsurface erosion. Enlargement of pipes (Fig. 2.9) can lead to tunnel formation and eventually collapse and the development of discontinuous bank gullies (Poesen, 1989; 1993). Despite its importance (see also Chapter 3), quantitative data on the susceptibility of soils to piping and the contribution of piping to sediment yield are scarce. Moreover, the methods for determining the susceptibility of soils to pipe development are not standardized. For this reason, there is a need for continued research on this phenomena and the development of a suitable laboratory test to better identify piping-prone soils. In the 1970's, Sherard et al. (1976a) proposed the pinhole test to evaluate the susceptibility of compacted fined-grained soils to piping erosion using a flow of water passing through a small hole (1 mm diameter) in a specimen under hydraulic heads (*H*) ranging between 50 and 1020 mm. However, this method is not entirely quantitative and it focussed on earth dam materials and not on natural soils. Therefore, the objectives of this work are: (i) to evaluate the effects of soil disturbance (disturbed and undisturbed soil samples), hydraulic head, water quality and antecedent soil moisture content (*ASM*) on the hydrological and erosion response of loess-derived soil materials during pipeflow; (ii) to evaluate the hydrological and erosion response of different types of loess-derived soil horizons: i.e. A_p and B_t horizons, decalcified loess (C_1) and calcareous loess (C_2); and (iii) to formulate recommendations and to draw conclusions about the suitability of the pinhole test to assess the susceptibility of soils to piping erosion. By testing the most contrasting soil horizons, the susceptibility of various loess-derived soil horizons in the Flemish Ardennes can be evaluated using these results as well (see Chapter 7).

** based on: Nadal-Romero, E., Verachtert, E., Maes, R., Poesen, J. 2011. Quantitative assessment of the piping erosion susceptibility of loess-derived soil horizons using the pinhole test. Geomorphology 135, 66-79.

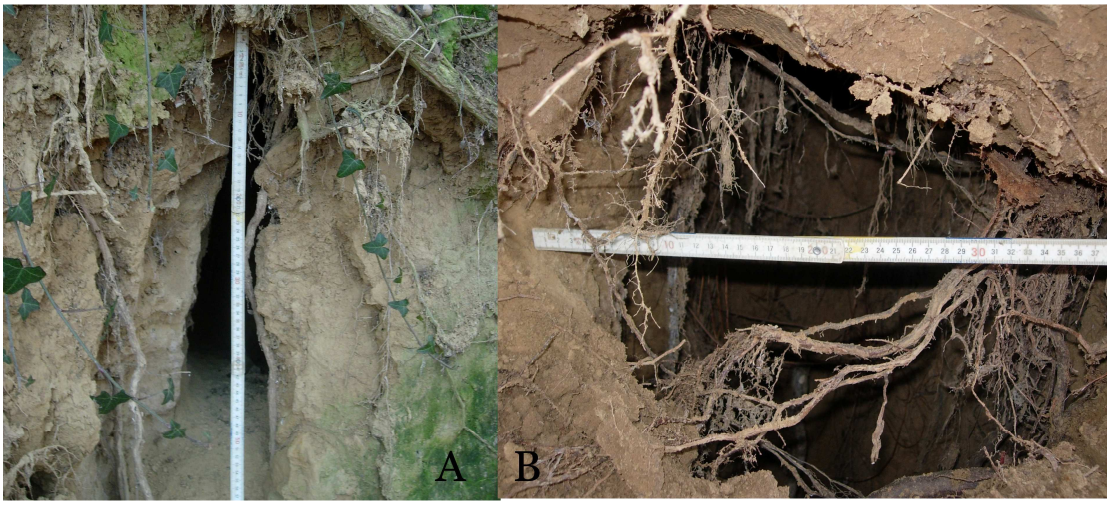


Fig. 2.9. Pipe development in calcareous loess (Korbeek-Dijle, February 2010).

2.2.2. The pinhole test: a review

The development of piping processes is generally associated with the presence of dispersive materials. Dispersion refers to the breakdown of the micro-aggregates into individual particles of sand, silt and clay (So, 2002). Previous studies clearly demonstrated the importance of the interaction between exchangeable sodium and electrical conductivity (EC) in determining clay dispersion and piping processes (e.g. Quirk and Schofield, 1955; Rengasamy et al., 1984; Turner et al., 2008). However, exchangeable sodium is nearly absent in the loess-derived soils tested in this study. Specific tests such as the crumb test (Emmerson, 1967), the dispersive test (Sherard et al., 1972) and the pinhole test (Sherard et al., 1976a) have been proposed to evaluate the dispersion potential of compacted fine-grained soils. The pinhole test was first reported in the 1970's to identify and to improve the understanding of dispersive, sodium-rich and highly erodible fine-grained soils, mainly for studies of earth dam constructions and other structures in Australia (Sherard et al., 1976a, b).

Details of the test are given by Sherard et al. (1976a) and the procedure is based on extensive trials and observational experience. The pinhole test is performed by circulating water flow through a small hole (1 mm diameter) punched in an earth specimen under hydraulic heads (H) ranging between 50 and 1020 mm (Fig. 2.10). According to the original test procedure, soil samples must be preserved at their natural water content. Then, the natural water content of the specimen is measured and the water content is brought to near the plastic limit (Atterberg limit, by adding the required volume of water or by gradually drying). The 3.8 cm long sample is compacted in the cylinder on top of pea gravel and wire screen. Distilled water is forced to flow through the soil sample (horizontal cylinder) during 5 to 10 minutes under each *H*. The test is conducted by gradually increasing *H* from 50 mm, 180 mm, 380 mm to 1020 mm. The hydraulic heads applied were chosen as being convenient for the use in the laboratory and because they generate velocities of flow (0.305 m s^{-1} - 3.05 m s^{-1}) which approximate the initial velocity that might be expected in leaks within earth dams and other structures (Sherard et al., 1976a). According to Sherard et al. (1976a) the pinhole test is highly reproducible and the results of each individual test can be categorized easily. After the test, the earth material is classified into the six categories shown in Table 2.1, based on the final flow discharge through the specimen (cm^3 s^{-1}) and visual inspection of the effluent colour, and hole size at the end of the test (mm).

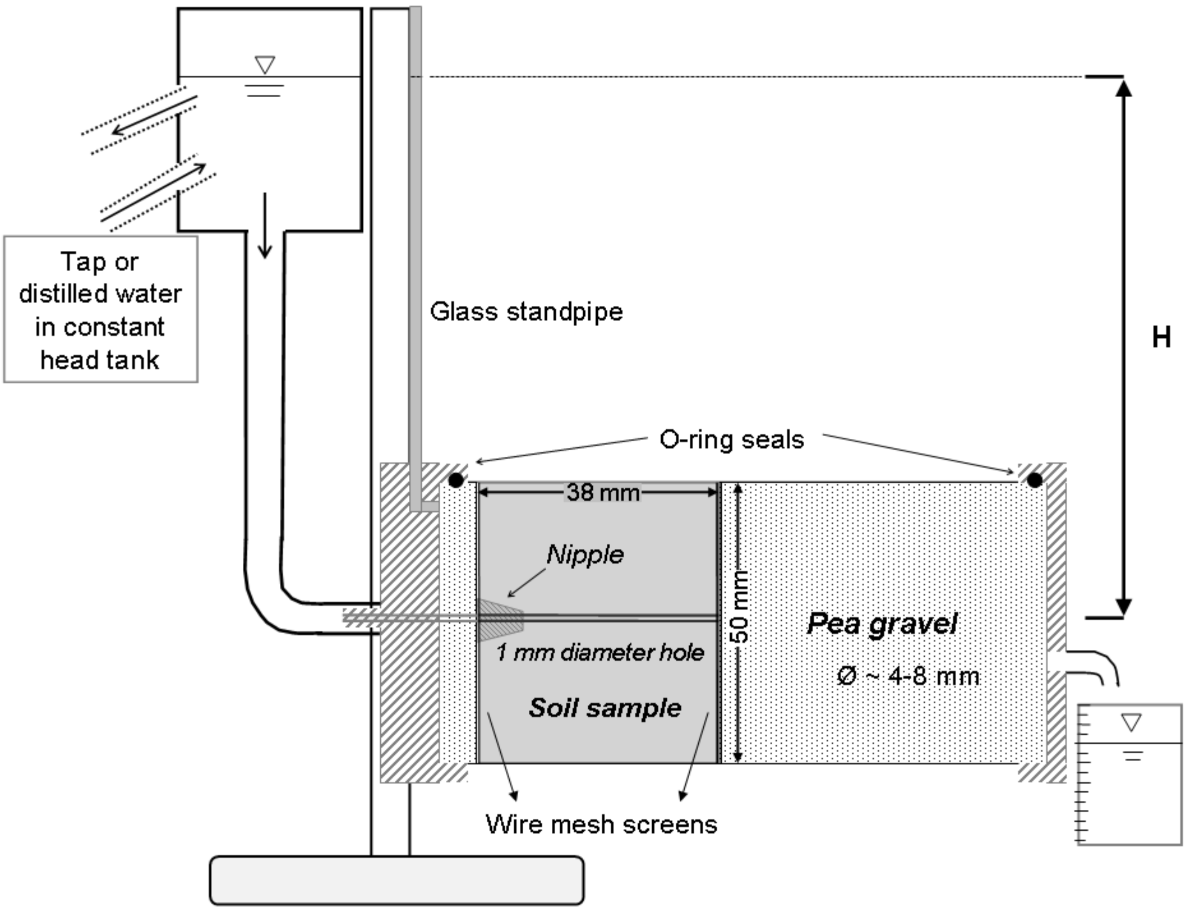


Fig. 2.10. Sketch illustrating the pinhole test set up. *H* = hydraulic head.

After some years, the test was used by engineers worldwide, reporting problems when setting up the apparatus, carrying out the test or interpreting the results (i.e. Evans, 1977; Schafer, 1978; Evans and Bell, 1981; Goldsmith and Smith, 1985; Leonards et al., 1991; Botschek et al., 2002a, b). The original pinhole test was devised for the purpose of identifying dispersive clays and it was not intended to be used as a quantitative test for measuring subsurface erosion rates. Therefore, the test has been mainly criticized for being a qualitative test (i.e. Acciardy, 1982; Jermy and Walker, 1999) and for not identifying true dispersion (i.e. Whaler and Arulanandan, 1976; Bell et al., 1986). Different proposals were made to provide a more quantitative measurement rather that the previous qualitative assessment based on visual examination by: (i) modifying the pinhole test classification (e.g. Acciardy, 1982; Glassey, 1986; Yetton, 1986), (ii) including a turbidity meter to provide a more accurate determination of piping initiation (i.e. Arulanandan and Heinze, 1977; Jermy and Walker, 1999), or (iii) modifying the device by adding a special metal disk with a short conical inlet pipe to prevent erosion on the upstream face of the sample (Rahimi and Abbasi, 2008). However, the pinhole test has also been reported as the most reliable method for identifying dispersive soils (e.g. Forstythe, 1977; Tosun, 1997; Bell and Walker, 2000; Vacher et al., 2004b; Batog et al., 2007) because it could correctly simulate the state of the soil and the water chemistry simultaneously (Mitchell, 1993). Other advantages reported are the reproducibility (Marshall and Workman, 1977), usefulness for erosion models (Lim, 2006), and the suitability for identifying dispersive soils (Reeves et al., 2006; Fauzilah et al., 2008) or tunnelling processes (Vacher et al., 2004b).

Table 2.2 presents general information of a selection of the studies reviewed. An analysis of these studies reveal that: (i) materials and soils selected in the different studies are highly variable; (ii) in general, most studies conducted the laboratory experiments under natural soil water contents, although it presented high variability and ranged between 6 and 70%, depending on the soil type, and the study area; (iii) most tests were performed at four different hydraulic heads (50, 180, 380 and 1020 mm), although there are some exceptions; (iv) distilled water was used as a basis of comparison in the different investigations; and (v) dominantly semi-quantitative observations were reported in all the studies: flow discharge, effluent colour and appearance and final size of the hole after the test. Table 2.2 also presents the main objectives and purposes of the studies reviewed. In most cases, the objective was to

Table 2.1. Classification and categories of the dispersivity of soils based on the pinhole test results (based on Sherard et al., 1976a). H is hydraulic head.

Classification of individual tests results	*H* (mm)	Final flow discharge through specimen ($cm^3\ s^{-1}$)	Colour of flow at end of the test (cloudy or colour)	Pipe hole diameter after test (*n* x needle diameter)	Classification of soil samples
D1	50	> 1.5	Very distinct	2x	Dispersive soils: fail rapidly under 50 mm head
D2	50	> 1.0	Distinct to slight	2x	
ND4	50	< 0.8	Slight but easily visible	1.5x	Intermediate soils: erode slowly under 50 mm or 180 mm head
ND3	180-380	> 2.5	Slight but easily visible	2x	
ND2	1020	> 3.5	Clear or barely visible	2x	Nondispersive soil: no colloidal erosion under 380 mm or 1020 mm head
ND1	1020	< 5.0	Crystal clear	1 (no erosion)	

Table 2.2. Overview of studies reporting the use of the pinhole test for solving engineering (ENG) or geomorphological (GEOM) problems. In all these tests susceptibility of various types of soils or sediments to dispersion or piping were observed by measuring water flow discharge, effluent colour and appearance and final size of the pinhole after the test. N.A. = Not available; DW = distilled water.

Source	Objectives	Study area	Soil material	Soil moisture content	Hydraulic head (mm)	Water quality
Sherard et al. (1976a, b)	ENG: to summarize a previous investigation about dispersive clays and its relation with failed dams	Australia	Fine-grained soil	Natural water content	50-180-380-1020	DW
Schafer (1978)	ENG: to modify the test procedure: pinhole test to determine dispersive clays	Port Hills, New Zealand	Loessial soils	Natural water content	50-180-380-1020	DW
Head (1982)	ENG: to identify dispersive clays	N.A.	N.A.	Natural water content-plastic limit	50-180-380-1020	DW
Goldsmith and Smith (1985)	GEOM: to discuss factors involved in the formation of subsurface erosion tunnels; to present the results of a study on natural subsurface erosion tunnelling in Pleistocene sediments	South Auckland, New Zealand	Waitemala Group soils (silts and clays)	Natural water content (39-70%)	50-180-380-1020	DW
Leonards et al. (1991)	ENG: to describe the test results, and to draw conclusions regarding the effects of fly ash in the reservoir on potential piping and erodibility of the compacted clay blanket	West Virginia, USA	Upstream Clay Blanket: compacted weathered shale	Natural water content	50-800	DW
Tosun (1997)	ENG: to present different tests (used of Earthfill dams) to determine the dispersivity properties of soils and discuss their limitations	29 different dams in Turkey	Fine-grained clayey and silty soils	N.A.	50-180-380	DW
Botschek et al. (2002a, b)	GEOM: to study the suitability of various physical and chemical soil indicators of piping susceptibility	Bergisches Land (Bonn area), Germany	Loamy solifluction deposits of non-calcareous loess	Specific Moisture: 200 g/kg	20-50-300	DW

Vacher et al. (2004a, b)	ENG: to report the development of a laboratory-based testing procedure to characterise the risk of tunnelling failure	Australian mines	Mine Spoil Material	Natural water content-plastic limit	50-180-380-1020	DW
Batog et al. (2007)	ENG: to describe a test method for a direct qualitative measurement of the dispersivity of clayey soil to be used to reconstruct Odra river embankments	Odry river, Poland	Cohesive soils	N.A.	50-180-380-1020	DW
Fauzilah et al. (2008)	GEOM: to determine the mechanism of internal erosion resistance against soil slope instability. Different tests were conducted to investigate the soil dispersivity characteristics	UiTM's University campus, Malaysia	Sedimentary residual soil: fine-grained	Natural water content (15-34%)	50-180-380-1020	DW
Muttuel (2008)	ENG: to improve the understanding of the soil erodibility, when evaluating the safety of engineering structures. To measure the dispersivity of compacted fine-grained soils	New South Wales, Australia	Silty sand and dispersive clay	Optimum water content	N.A.	DW
Rahimi and Abassi (2008)	ENG: to study the causes of concrete lining destruction of the main canal of the Saveh Irrigation project	Markazi Province, Iran	Fine sandy soils	Natural water content (6-22%)	N.A.	DW

identify the dispersivity of soils, in relation to civil engineering constructions (i.e. dams, irrigation canals…), and recently, some of them present different laboratory tests to determine dispersive clays and soils and to evaluate the susceptibility to subsurface erosion (e.g. Botschek et al., 2002a, b; Fauzilah et al., 2008). However, the use of the pinhole test in geomorphological studies is very limited.

2.2.3. Materials and methods

2.2.3.1. Laboratory pinhole test

The overall methodology followed is that proposed by Sherard et al. (1976a), except for the adaptations reported below to test both disturbed and undisturbed soil samples and to obtain quantitative data. Some adaptations related to the preparation of the samples were introduced because the original procedure for earth dam materials was not suitable for comparing natural soils. For disturbed samples, the methodology followed is that proposed by Nadal-Romero et al. (2009). Prior to each pinhole experiment the soil was collected in the field and it was air-dried at room temperature (20℃) for 3 days and sieved using a me sh size of 1.25 cm diameter. In order to obtain standardized natural compaction conditions, rainfall simulation was used. An interrill erosion plot box (Poesen et al., 1990) with a central test area of 0.60 x 0.94 m^2 was filled over a depth of 15 cm with the sieved soil (Fig. 2.11a). Simulated rainfall with an intensity of 67 mm h^{-1} was then applied for one hour to slightly compact the topsoil. After one hour of drainage, undisturbed soil samples were taken using stainless steel rings with a diameter of 5 cm and a length of 8 cm (Fig. 2.11b). By pushing the steel rings 4 cm deep into the sealed and compacted soil, 4 cm long soil samples at a standardised preparation were obtained (volume of 78.5 cm^3). The remaining length of the steel rings was filled with wire mesh screens and pea gravel.

Besides the adapted procedure for disturbed samples, the test was carried out with undisturbed samples as well. In order to obtain undisturbed soil samples, the metal cylinders (5 cm in diameter and 8 cm high) were inserted horizontally into the soil profile and dug out by hand or with a small trowel. Then the samples were packed in plastic bags to keep their moisture content constant (4 cm long soil samples with a volume of 78.5 cm^3). At the time of soil sampling, 3 additional cylindrical samples (stainless steel rings 5 cm high and 5 cm diameter, 98.17 cm^3) were also collected to determine the antecedent soil moisture content (*ASM*, g g^{-1}) and the bulk density (g cm^{-3}).

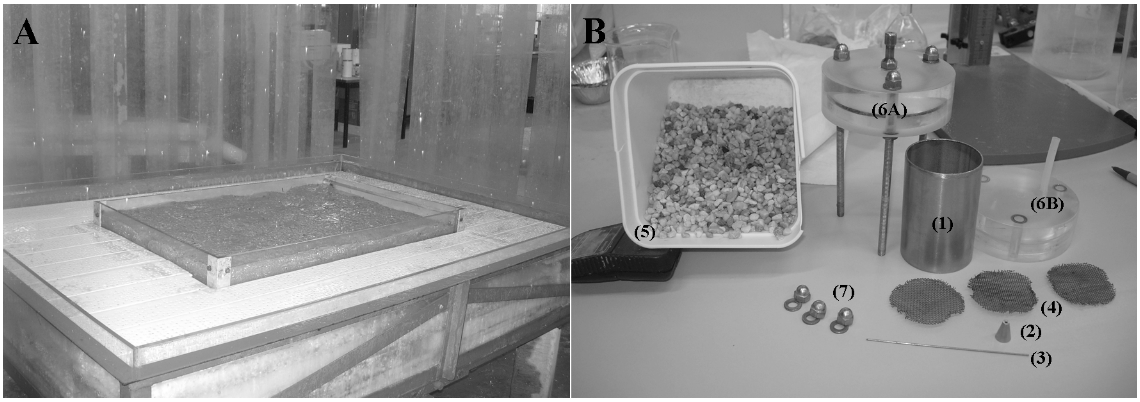


Fig. 2.11. (A) Rainfall simulation on interril flume with the central test area (0.60 x 0.94 m^2) filled with over a depth of 15 cm of the sieved soil horizon to be tested. (B) The component parts of the pinhole device: (1) Steel cylinder to be filled over a length of 4 cm with the soil to be tested; (2) metal nipple, in the form of a truncated cone with a 1.5 mm hole; (3) hypodermic needle, having a diameter of 1 mm, which is pushed axially through the soil sample; (4) three wire mesh screens; (5) pea gravel, ca. 5 mm in size; (6) cylindrical plastic body; (7) three washers and nuts to close the cylindrical body.

To provide a more quantitative assessment of piping susceptibility, the pipeflow discharge (Q_w, cm^3 s^{-1}) and the sediment load (Q_s, g s^{-1}) were measured every minute during a five minutes period starting immediately at the start of the outflow. The effluent was collected during one minute intervals with cylindrical measuring flasks, and sediment samples were then oven-dried at 110℃ during 24 hours. Observations of effluent colour and visual inspection of the pipe hole after the completion of the test were made as well. To better understand the effect of water quality on soil piping erosion, both tap water and distilled water (having an EC of 800 and 26 µS cm^{-1} respectively) were used in the different tests. The tap water has a pH of 6.9, a very low Sodium Adsorption Ratio (SAR = 0.34; www.vmw.be) and is calcareous. Finally, we conducted these tests at different antecedent soil moisture contents to understand the effect of water content on the hydrological and sediment response while Sherard et al. (1976a) used to work on wet samples around the Atterberg plastic limit.

A first series of pinhole test experiments was conducted to evaluate the effects of hydraulic head (*H*), water quality and *ASM* (soil samples were oven-dried at 30℃ for different time intervals) using silt loam top soil (A_p horizon) from Central Belgium sampled on a cropland. Three soil sample replicates for each combination of water quality, *H* and *ASM* were carried out: i.e. tap water and distilled water and 4 *H* values (50, 180, 380 and 1020 mm, based on Sherard et al., 1976a). In contrast to the procedure proposed by Sherard et al. (1976a), a new soil sample was used for each *H*. For the first series, 120 pinhole test experiments were conducted. A second series of pinhole test experiments was carried out in order to evaluate the effect of soil disturbance on the hydrological and sediment response of the B_t, decalcified loess (C_1) and calcareous loess (C_2) horizons (described in section 3.3) for different hydraulic heads and soil moisture contents using distilled water. A total of 135 pinhole test experiments were conducted in the second series. Finally, in order to assess the suitability of the pinhole test to determine the susceptibility of different soils to piping erosion, and to evaluate the hydrological and erosion response of different loess-derived soil horizons (i.e. A_p, B_t, decalcified loess (C_1) and calcareous loess (C_2)), a two series of comparison tests were made.

2.2.3.2. Statistical analysis

All statistical analyses were performed using the statistical software SPSS (PAWS statistics 18.0 for Windows). The effects of soil disturbance, hydraulic head, water quality and antecedent soil moisture content and the time to outflow, pipeflow discharge and sediment discharge response were analysed with linear regressions and analysis of variance (ANOVA). These analyses were also used in order to assess the differences in hydrological and sediment response among the different loess-derived soil horizons.

2.2.3.3. Study sites and loess-derived soil horizons

The samples are taken at study sites near Leuven, in the Belgian loess belt. The loess covers Tertiary sandy deposits and the depth of the loess cover ranges between a few centimetres and 10 m (Goossens, 1993). It is a plateau with a mean altitude of 115 m and a gently sloping topography to the North (Evrard et al., 2008). The climate is temperate humid with well-distributed precipitation (ca. 750 mm) with high intensity peaks in summer (Bollinne, 1982). Soils in the region are mainly

Luvisols, formed after deposition of the loess in the late Pleistocene and resulting from decalcification and clay mobilisation (FAO, 1998). The typical sequence of soil horizons from the top to the bottom is: (i) a cultivated topsoil (A_p), (ii) a clay-enriched horizon (B_t), (iii) a decalcified loess horizon (C_1), and (iv) a calcareous loess (C_2, parent material).

The silt loam topsoil (A_p horizon) used in the pinhole experiments was excavated in Heverlee (50° 52’ 12” N, 4° 39’ 01” E) at a depth o f 0-0.50 m (Smets, 2009). It is representative for croplands where the topsoil is still present and it has an organic matter content of 1.9% (Smets, 2009). Soil sampling of the other horizons for this study was carried out at two locations. At site A (Bertem, 50° 52’ 42.29” N, 4° 39’ 14.77” E, Fig. 3B and 3C) the B_t horizon was sampled at 0.40-0.60 m below the surface. At site B (Korbeek-Dijle, 50° 50’ 04.49” N , 4° 37’ 53.03” E, Fig. 3D and 3E) the C_1 and C_2 horizons were sampled in a typical sunken lane in the loess belt. All horizons consist mainly of silt (> 70%, Table 2.3) and the textures (obtained with LS 13 320 Laser Diffraction Particle Size Analyser of Beckman Coulter) are all silt loams. The B_t horizon is significantly enriched in clay. The calcareous loess (C_2 horizon) contains up to 14% calcium carbonate (obtained by weight loss following decalcification with HCl) which is present primarily as detrital grains.

Table 2.3. Texture, dry bulk density (BD) and $CaCO_3$ content of the loess-derived soil horizons studied.

Soil horizons	% Clay (0-2 µm)	% Silt (2-63 µm)	% Sand (> 63 µm)	BD (g cm^{-3})	$CaCO_3$ (%)
A_p	12	80	8	1.5	0
B_t	20	74	6	1.37	0
C_1	7.9	79.8	12.3	1.34	0
C_2	8.8	79.8	11.4	1.34	14.6

2.2.4. Results and discussion

2.2.4.1. Evaluation of the pinhole test

The effect of different sampling and preparation methods (soil disturbance), hydraulic heads, water qualities and antecedent soil moisture content are reported in detail in Nadal-Romero et al. (2011). The following trends were observed.

(i) *A significant increase of pipeflow and sediment discharge with increasing hydraulic head ($p < 0.05$)*. The correlation was stronger for Q_w than for Q_s (Fig. 2.12). Soil particles were mobilized at 50 mm head but not exported from the soil sample because of the very low transporting capacity of the pipeflow. Higher hydraulic gradients (380 and 1020 mm) produced intense throughflow rates. Foster et al. (2002) found that the hydraulic gradient is not nearly as important as other factors involved in piping failures, such as potential seepage paths along conduits and structures. We suggest the use of two different and contrasting hydraulic heads (i.e. 180 and 1020 mm) to produce different pipeflow shear stress: a small H to detect which horizons are already susceptible at low hydraulic heads and H = 1020 mm because field observations indicate that earth banks may have heights of >1 m.

(ii) *Water quality (tap water versus distilled water) has no significant effect on pipeflow discharge but the sediment is more transportable when distilled water is applied (Fig. 2.12).* This is in agreement with results on susceptibility of silt loam soils to physical degradation under rainfall simulations using tap and distilled water (Borselli et al., 2001). These authors stated that the water quality used in laboratory simulations needs to match that of rainfall and they concluded that good quality water should always be used for every type of soil. Since the tap water quality may vary a lot, we suggest the use of distilled water to determine realistic values of hydrological and erosion parameters and for comparisons (relative ranking, classifications…) between different soils or soil horizons.

(iii) *No statistical relationships were observed between ASM and Q_w, however, Q_s decreased with increasing ASM*. The high values of sediment discharge with the lowest antecedent soil moisture content could be explained by slaking followed by dispersion. Similarly, the negative relationship observed in the present study has also been demonstrated for loess-derived soil horizons subjected to concentrated flow erosion (e.g. Govers et al., 1990; Govers, 1991; Nachtergaele and Poesen, 2002; Knapen et al., 2007). Sherard et al. (1976a) indicated that drying and rewetting soil samples apparently causes a temporary condition of disequilibrium in the interaction forces between clay particles, which could give variable results in the pinhole test. In this context, Schafer (1978) indicated that air drying probably influences dispersive behaviour of a soil and that curing after compaction may change pinhole test results in the direction of increased dispersion resistance for soils that have been air-dried and rewetted. We propose the use of different antecedent soil moisture contents (dry versus wet) to assess the influence of soil moisture content on the hydrological response and on the resistance to subsurface erosion.

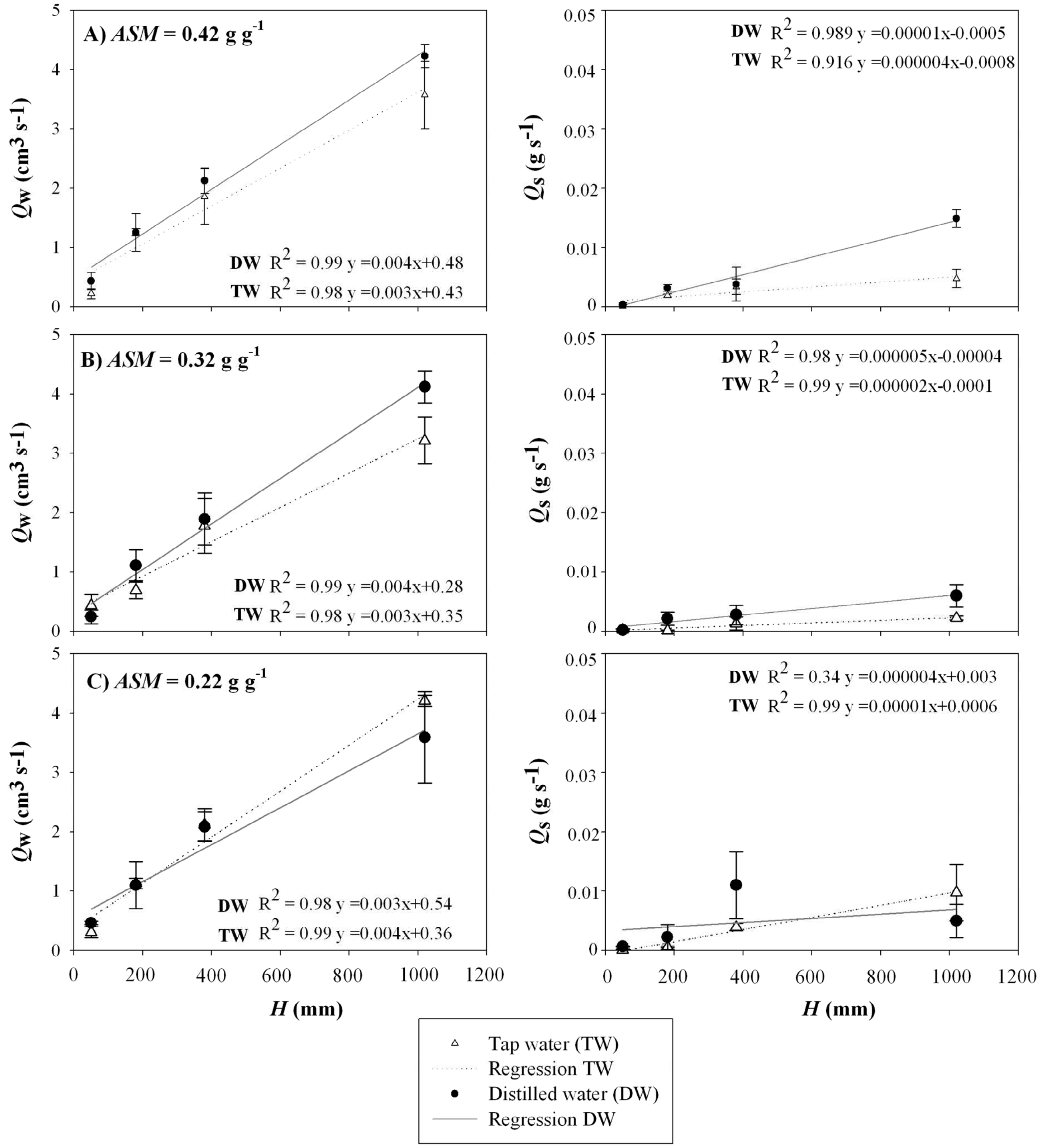


Fig. 2.12. Effect of hydraulic head (*H*) on mean pipe flow discharge (Q_w) and mean sediment discharge (Q_s) (n = 3 replicates) at different antecedent soil moisture contents (*ASM*) for tap water (TW) and distilled water (DW) for the disturbed A_p horizon. Error bars indicate the minimum and maximum values.

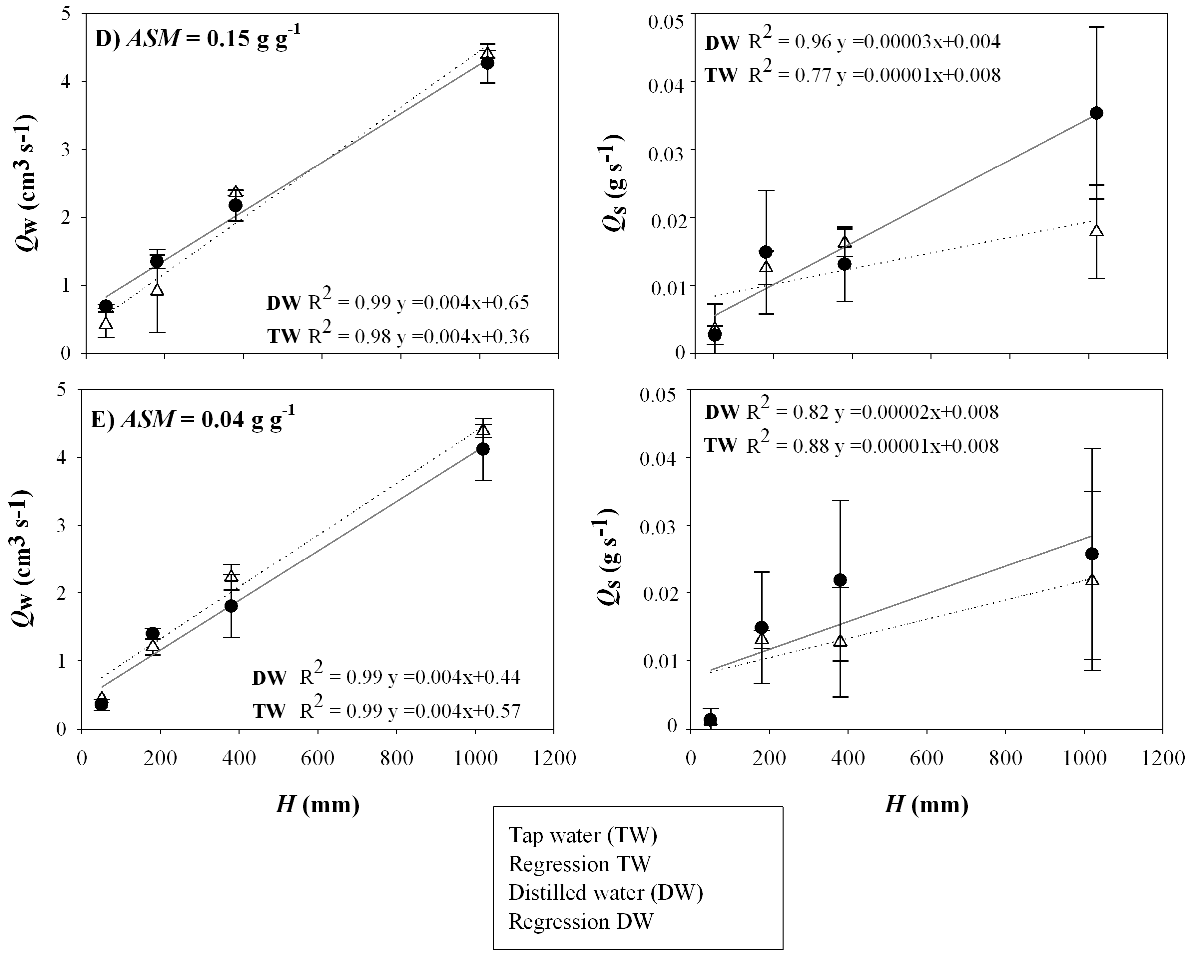


Fig. 2.12 continued. Effect of hydraulic head (*H*) on mean pipe flow discharge (Q_w) and mean sediment discharge (Q_s) (n = 3 replicates) at different antecedent soil moisture contents (*ASM*) for tap water (TW) and distilled water (DW) for the disturbed A_p horizon.

(iv) *Disturbed soil samples showed more rapid pipeflow and lower Q_s than undisturbed soil samples (Fig. 2.13)*. We recommend the use of both sample preparations to test the influence of soil disturbance on different soils, especially for assessing the erosion response.

Apart from the semi-quantitative assessment based mainly on visual examination (hole size, colour of the flow, pipeflow discharge), our study concludes that the pinhole test is suitable for assessing the susceptibility of soil horizons to piping in a quantitative way by means of pipeflow discharge (Q_w) and sediment discharge (Q_s) measurements. The experiments demonstrate that it is a reliable test for discerning dispersive from non-dispersive soils, although it does not yield an erosion index. The authors recommend the test because it is (i) highly reproducible, (ii) relatively fast (around 10 minutes for each individual soil sample), (iii) inexpensive (although the availability of large quantities of distilled water is necessary) and (iv) only small soil samples are needed (the soil sample volume was around 78.5 cm^3).

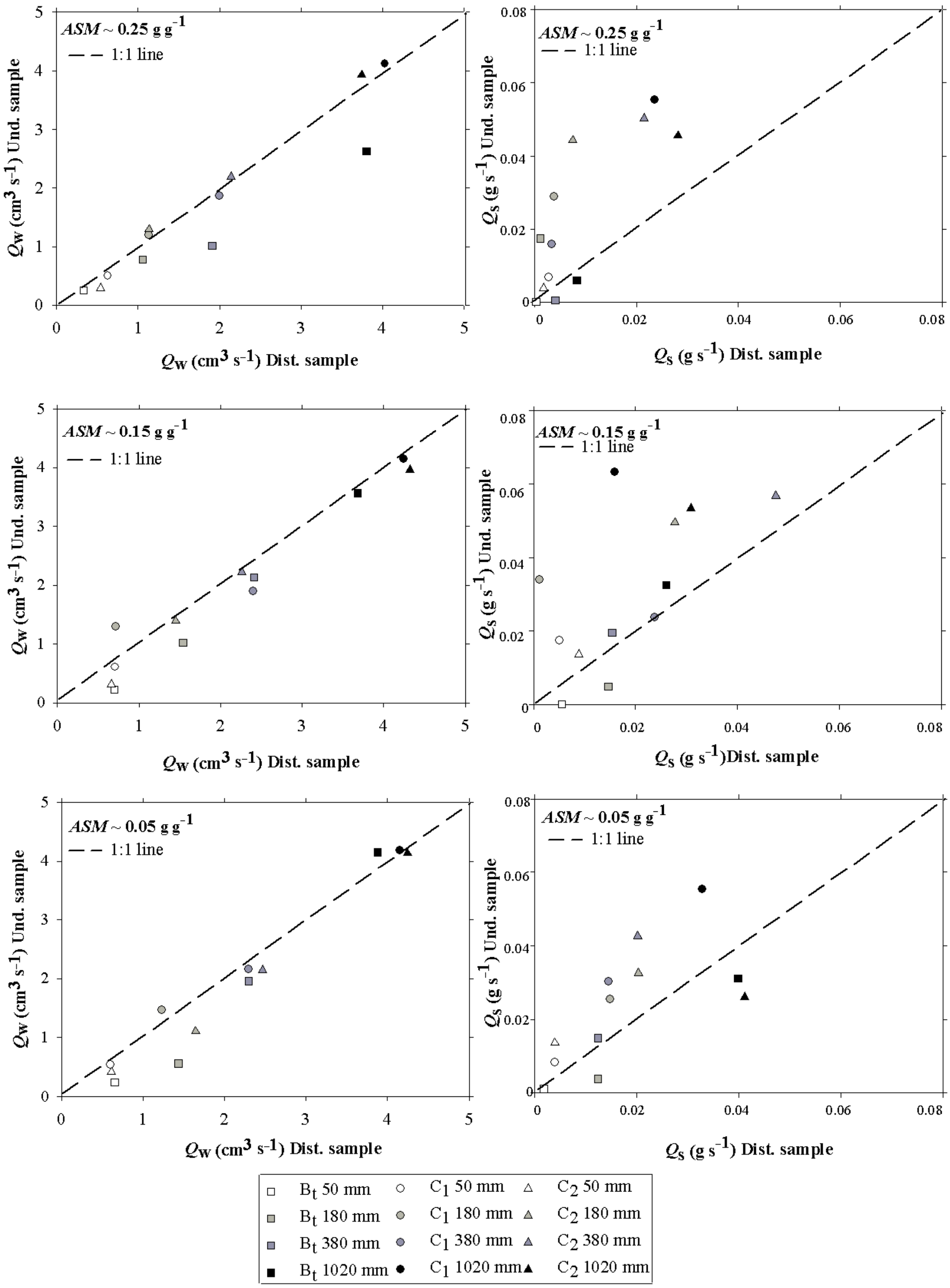
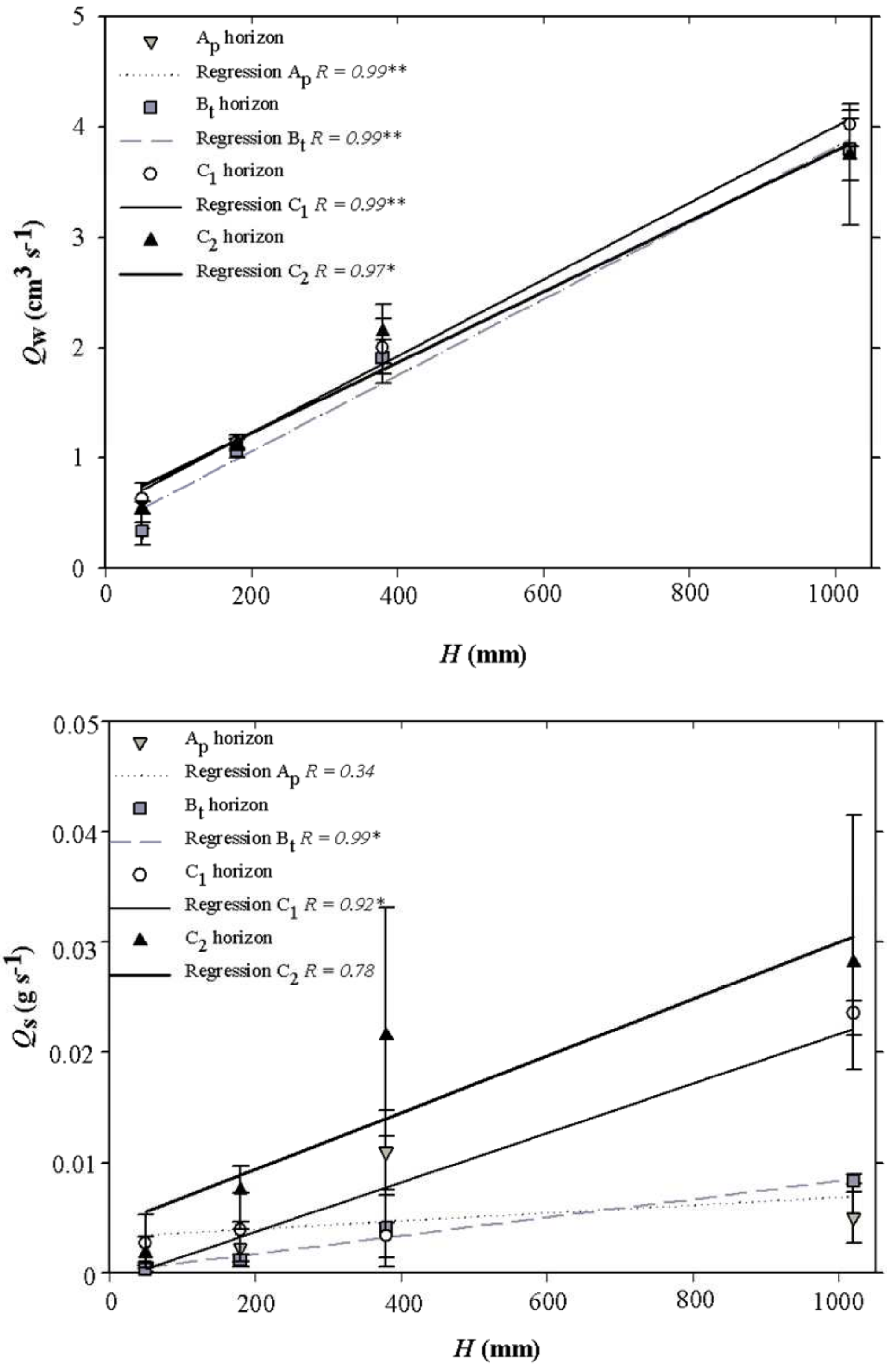


Fig. 2.13. Comparison of mean pipe flow discharge (Q_w) and mean sediment discharge (Q_s) (n = 3 replicates) for disturbed and undisturbed soil samples from three loess-derived soil horizons at different hydraulic heads (H = 50, 180, 380 and 1020 mm), and at different antecedent soil moisture content (ASM ~ 0.25, 0.15 and 0.05 g g^{-1}), using distilled water.

2.2.4.2. *Using the pinhole test to compare piping erosion susceptibility of different loess-derived soil horizons*

Using disturbed samples, Fig. 2.14 compares mean Q_w and mean Q_s of the different disturbed loess-derived soil horizons (A_p, B_t, C_1 and C_2) for varying *H*. The mean Q_w of the different horizons was not significantly different for disturbed nor for undisturbed samples (Table 2.4). For Q_s (Fig. 2.14b), greater differences between horizons and a larger variability, especially for the C_2 horizon, were observed. Also the undisturbed C_2 horizon showed a significantly higher erosion response than the disturbed samples of the upper horizons (A_p, B_t and C_1; Table 2.4). Also for undisturbed samples, mean Q_s values corresponding to C_1 and C_2 horizons were significantly higher compared to B_t values. After the test was carried out, additional evidence for soil erodibility was used, i.e. a visual inspection of the specimen as a criterion to assess soil erodibility (Sherard et al., 1976a, b). However, there were problems to correctly identify the final eroded pinhole size (e.g. collapse of the hole) and it was only possible to measure the hole dimension in 43.5% of the experiments. These measurements indicate that (Table 2.5): (i) the diameter of the hole after the test is larger with increasing H, and (ii) the calcareous horizon (C_2) showed the highest dispersion resulting in the largest holes after the experiments (see Fig. 2.15).

(a)



(b)

Fig. 2.14. Effect of hydraulic head (H= 50, 180, 380 and 1020 mm) on (a) mean pipeflow discharge (Qw) and (b) mean sediment discharge (Qs) (n= 9) for 4 disturbed loess-derived soil horizons using distilled water. Vertical bars represent minimum and maximum values.

Table 2.4. Statistical comparison of the mean values of pipeflow discharge (Q_w) and sediment discharge (Q_s) corresponding to the different loess-derived soil horizons (A_p, B_t, C_1 and C_2) for undisturbed and disturbed soil samples.

	Q_w (cm^3 s^{-1})		Q_s (g s^{-1})	
	Disturbed	Undisturbed	Disturbed	Undisturbed
A_p	1.81 a	N.T.	0.003 b	N.T.
B_t	1.78 a	1.64 a	0.005 b	0.006 b
C_1	1.95 a	1.92 a	0.008 b	0.027 a
C_2	1.93 a	1.89 a	0.015 a	0.036 a

Within each column, the horizons with a different letter differ significantly ($p < 0.05$) based on Bonferroni test, with a >b; N.T. = Not tested.

Table 2.5. Mean diameter and standard deviation (mm) of the hole after running the pinhole test for undisturbed and disturbed samples at different hydraulic heads (*H*) for the different loess-derived soil horizons. *n* = number of samples (total number of samples measured = 111). N.T. = Not tested.

	Undisturbed soil samples				Disturbed soil samples			
H	A_p	B_t	C_1	C_2	A_p	B_t	C_1	C_2
50 mm	N.T.	1±0.0	1.7±0.6	1.5±0.5	1.8±0.2	1.5±0.5	1.5±0.5	1±0.0
n	N.T.	2	3	6	12	5	5	6
180 mm	N.T.	1.8±0.3	1.7±0.3	2.5±0.5	2±0.4	1.8±0.3	1.5±0.4	1.7±0.3
n	N.T.	3	2	3	11	5	5	2
380 mm	N.T.	2	2±0.0	2.7±0.3	2.2±0.5	2.2±0.5	2.2±3	2.3±8
n	N.T.	1	2	2	6	4	3	3
1020 mm	N.T.	2±0.0	2.5±0.5	3±0.0	2.1±1.1	2.7±0.6	2.5	3±0.0
n	N.T.	2	3	2	5	5	1	2

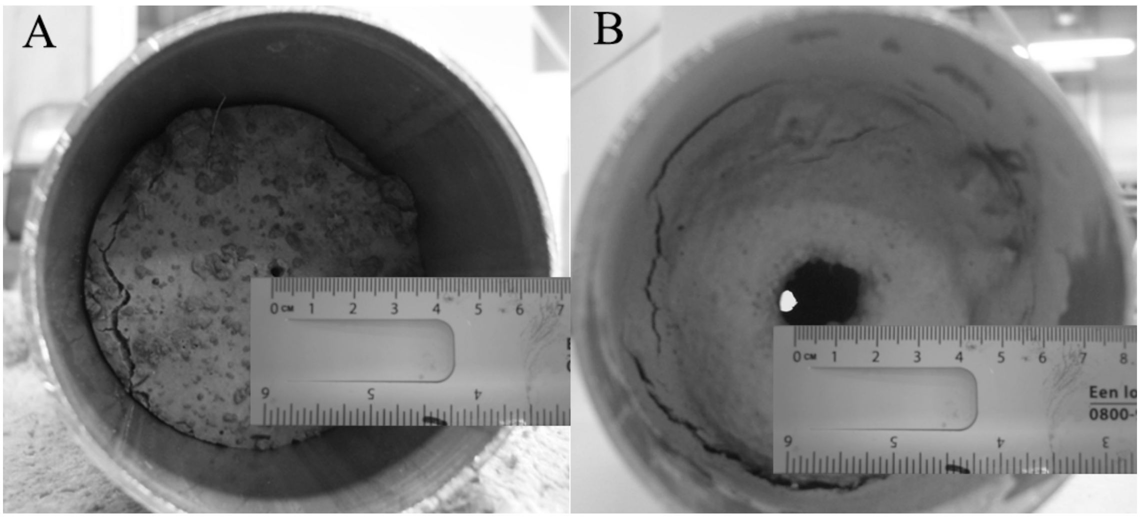


Fig. 2.15. Disturbed loess-derived soil samples with pipe holes after pinhole test for a B_t samples (A) and a C_2 sample (B).

Based on the classification of Sherard et al. (1976a), the decalcified loess (C_1) and calcareous loess (C_2) correspond to D2 (dispersive soils), showing high susceptibility to piping, whereas the A_p and B_t horizons are ranked as ND4 (intermediate soils). Field observations confirm that the calcareous loess (C_2 horizon) has the highest susceptibility to piping. Peele et al. (1938) observed that the presence of finely dispersed calcium carbonate increased the instability of aggregates, while Barahona et al. (1990) found that the content of clay and silt-sized calcium carbonate in Spanish soils had a strong positive effect on its interrill erodibility. The lower erodibility of the B_t horizon may be explained by aggregates stabilized by a higher clay content (Attou et al., 1998). Sekera and Brunner (1943) confirmed also the low aggregate stability of the loess rich substratum and its high vulnerability to dispersion. Due to a very low organic matter content and a low clay content the calcareous loess (C_2 horizon) is highly susceptible to water erosion. The results of the pinhole test concerning subsurface erosion are in agreement with previous studies on surface water erosion of loess-derived soils concluding that erosion rates vary significantly between different soil horizons (Poesen and Govers, 1990; Poesen, 1993; Poesen et al., 1998; Nachtergaele and Poesen, 2002; Vanwalleghem et al., 2005). Vanwalleghem et al. (2005) reported that areas where the calcareous C_2 horizon crops out are more susceptible for deep gully development. Based on flume experiments, Nachtergaele and Poesen (2002) also showed quantitatively that the C_2 horizon is up to five times more erodible during concentrated flow than the B_t horizon.

2.2.5. Conclusions

This study aimed at evaluating the effects of sample preparation, hydraulic head, water quality and *ASM* on the hydrological and erosion response of loess-derived soil materials during pipeflow, to draw conclusions about the suitability and formulate recommendations for the use of the pinhole test in assessing piping susceptibility. The results demonstrate that the pinhole test is suitable for assessing the susceptibility of soil horizons to piping in a quantitative way (i.e. Q_w, Q_s, the time to outflow and the cross-section of the pipe after the test). We recommend the use of: (i) at least two distinct hydraulic heads (i.e. 180 and 1020 mm), (ii) distilled water, (iii) contrasting antecedent soil moisture contents of the soil samples to be tested, and (iv) different soil sampling methods to investigate the effect of soil disturbance, and particularly to obtain a better understanding of the sediment response during pipeflow.

Furthermore, the objective was to evaluate erosion response of contrasting loess-derived soil horizons. A typical soil profile on loess in Central Belgium showed an increase in pipeflow erosion rate with depth. According to the pinhole test experiments, quantitative data on the susceptibility to piping erosion for different loess-derived soil horizons indicated that the A_p and B_t horizons were at least two times more resistant than the C_1 and C_2 horizons. Based on the classification proposed by Sherard et al. (1976), the decalcified loess (C_1) and calcareous loess (C_2) were ranked as D2 (dispersive), which means they have a high susceptibility to piping, while the A_p and B_t horizon were ranked as ND4 (intermediate). In line with field observations and studies on gully erosion, the results confirm that most loess-derived soil horizons are susceptible to piping erosion, especially the calcareous loess horizon. Finally, this study indicates that the use of single hydrological and erodibility parameter values (Q_w and Q_s) when modelling erosion on loess-derived soils may lead to significant errors in predicted volumes and patterns of subsurface erosion. Future studies on soil erosion in loess areas should consider that different loess-derived soil horizons have variable susceptibilities to subsurface erosion. These different susceptibilities will be related to differences in antecedent soil water content and soil texture (as shown in the tests), but also to differences in inherent soil structure, organic matter, ionic strength and iron-clay colloidal build-up.

Chapter 3
Soil loss rates due to piping erosion *

3.1. INTRODUCTION

For several decades, assessments of soil erosion rates by water have mainly concentrated on sediment detachment and transport by overland flow, which is more visible and easy to quantify than subsurface flow. By contrast, piping occurs under specific geomorphological and climatological conditions (Faulkner, 2006), which limits the occurrence of piping to certain areas. Furthermore, pipes are only visible at the soil surface when a pipe roof collapses. Subsequently, pipes may develop into gullies after collapse. Hence, the combination of the limited set of conditions where piping can occur and the subsurface and transient nature of the process make that it is generally less observed and less studied. However, the importance of subsurface soil erosion can be significant, because the subsurface enlargement of pipes and subsequent gully development are often responsible for high soil loss rates (Bocco, 1991). Soil piping (tunnel erosion) refers to the formation of linear voids by concentrated flowing water in soils or unconsolidated sediments, which can cause collapse of the soil surface and formation of discontinuous gullies (Jones, 2004b). However, before roof collapse reveals the size of the excavated pipe, the process may well be in an advanced stage (Faulkner, 2006). Furthermore, not only gully development, but also mass movements can be significant secondary consequences of pipe enlargement, inducing high soil losses (Poesen, 1989; Bocco, 1991; Poesen et al., 2003; Faulkner, 2006). Bryan and Jones (1997) state that piping is far more widespread than has often been supposed, forming in virtually all climates, in organic and mineral soils, on undisturbed and agricultural land and in certain unconsolidated sediments and bedrock.

In contrast with the extensive knowledge about soil loss from sheet and rill erosion (e.g. Cerdan et al., 2006; Cerdan et al., 2010) or gully erosion (Poesen et al., 2003; Poesen et al., 2006), reports of estimates of soil loss due to subsurface erosion are

* based on: Verachtert, E., Maetens, W., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2011. Soil loss rates due to piping erosion. Earth Surface Processes and Landforms 36, 1715-1725.

scarce. Gullies that are caused by subsurface processes are known and studied for a long time, although quantification is not straightforward due to the large variety and complexity (Jones, 1987b). Quantifying the geomorphic significance of piping erosion was stated as a major difficulty by Bryan and Jones (1997). Nevertheless, attempts have been made to estimate the gully head retreat or gully extension rates caused by piping (Parker et al., 1990; Poesen et al., 1996). Pipes are increasingly monitored but the studies mostly focus on the hydrological aspect (e.g. Sidle et al., 1995; Uchida et al., 1999; Holden and Burt, 2002; Jones and Connelly, 2002). Subsurface flow through pipes can be a significant contributor to stormwater discharge (Jones, 2010). Sediment concentrations in pipeflow have been measured as well (e.g. Bryan and Harvey, 1985; Jones, 1987a; Botschek et al., 2000; Zhu et al., 2002), mainly for short periods ranging from a few storms (Bryan and Harvey, 1985; Zhu et al., 2002) to a month (Botschek et al., 2000). Alternatively, Zhu (2003) surveyed tunnel development over a period of 12 years in the loess plateau of China and found the net tunnel erosion to be at least 25-30% of the catchment sediment yield. Others who measured the volume of the tunnels and pipe collapses to estimate the soil volume that was lost, came to significant erosion rates as well (e.g. Kerényi, 1994; Beckedahl, 1998; Botschek et al., 2000; Romero Díaz et al., 2009). Despite these valuable results, quantification of the contribution of piping to soil loss is still limited to a few case-studies in a limited number of environments. Therefore, this study aims at estimating the contribution of soil loss due to piping erosion (Fig. 3.1) in an area of Belgium with loess-derived soils in a temperate humid climate. The soil loss estimates obtained for this specific environment are then compared to soil loss rates of natural and artificial subsurface pipes to assess the significance of soil loss by piping.

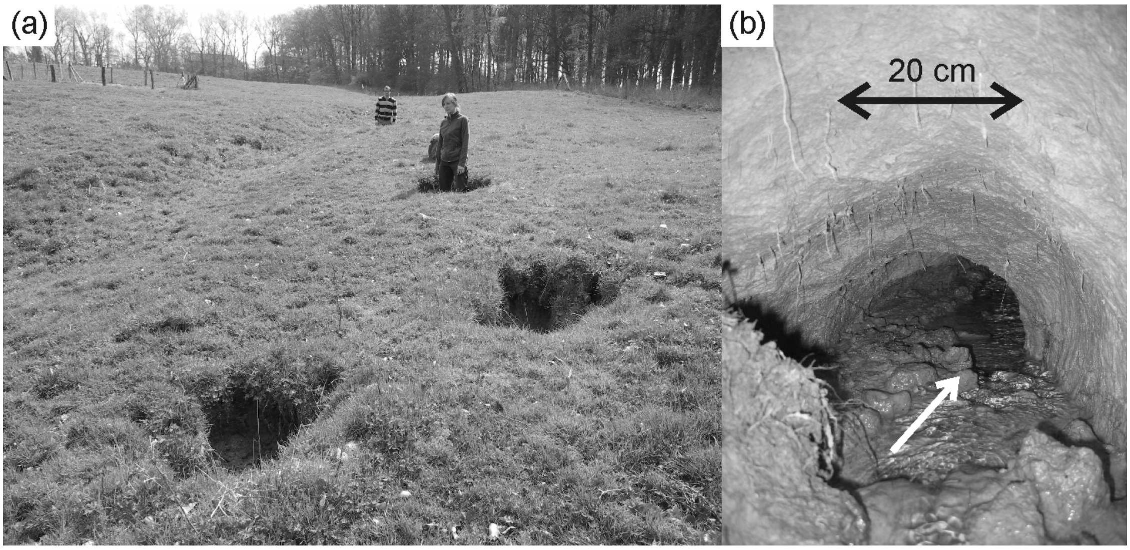


Fig. 3.1. (a) Typical collapsed pipes (n=4; diameter ca. 0.7 m; depth ca. 0.6 m) in a pasture (Kluisbergen, April 2009). Both persons are standing in a collapsed pipe. (b) Flow in a pipe, formed in silt loam colluvium with a typical semicircular cross-section (Fig. 3.5). The white arrow indicates the flow direction.

3.2. MATERIAL AND METHODS

3.2.1. Mapping of pipe collapses

Aerial photographs (orthophotos 1:12,000, taken in March; AGIV, 2006) were analyzed and the sites with indications of collapsed roofs of pipes (recognized as 'black spots' on the orthophoto) were selected for an intensive field check (Fig. 3.2). Furthermore, farmers and personnel of local technical services of the municipalities were interviewed. The field survey focused on pasture but during the enquiries farmers were also asked for piping phenomena under cropland. The forests within the study area were already checked for piping during recent research on landslides (Van Den Eeckhaut et al., 2005), but only one site with collapsed pipes was observed under forest. In total, 137 parcels having 560 collapsed pipes (CP) were mapped with GPS (Trimble 2005 GeoXT; accuracy < 1 m, Fig. 3.3) during field surveys in 2008-2009. The term parcel refers to a farmer's plot mostly limited by fences and ca. 1.5 ha large. Each group of interconnected CP within a parcel is named a site. The depth and diameter of the CP were measured using a folding rule.

Fig. 3.2. Photographs of the study area. (a) Aerial orthophoto with indications of possible collapsed pipes. (b and c) Terrestrial photos of the sites with collapsed pipes (Kluisbergen, December 2007; see (a) for location).

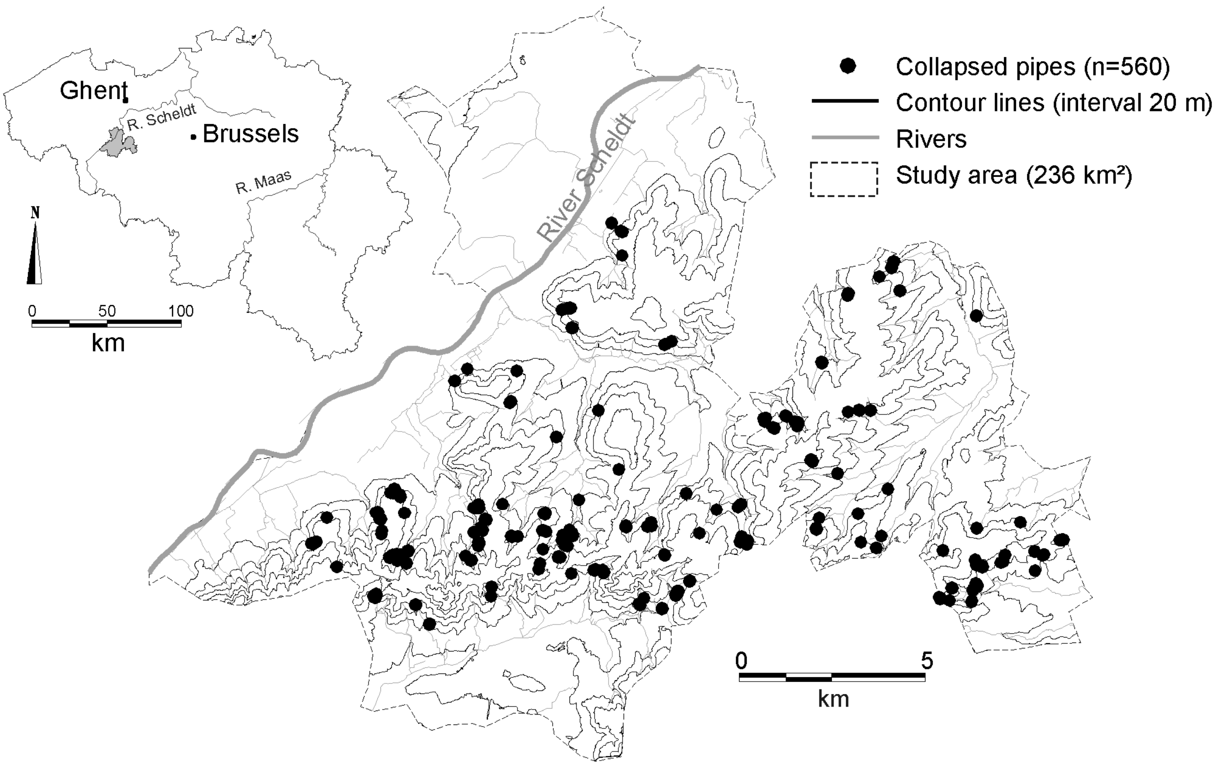


Fig. 3.3. Location of the study area in Belgium and the collapsed pipes (*n* = 560) projected on a map with indication of the contour lines and rivers.

3.2.2. Soil loss calculation

A classification of piping features was made based on their morphological characteristics (see section 3.3.1.), allowing for different volume calculations. The depth (D) and diameter (2r) of the CP were measured using a folding rule. For each parcel with CP, the volume lost due to piping was estimated (Fig. 3.4) as:

$$V = \sum_i V_i + L.A_p \quad (3.1)$$

with V_i volume (m³) of one collapsed pipe, L length of the pipe (m), A_p mean cross section (m²) of a pipe.

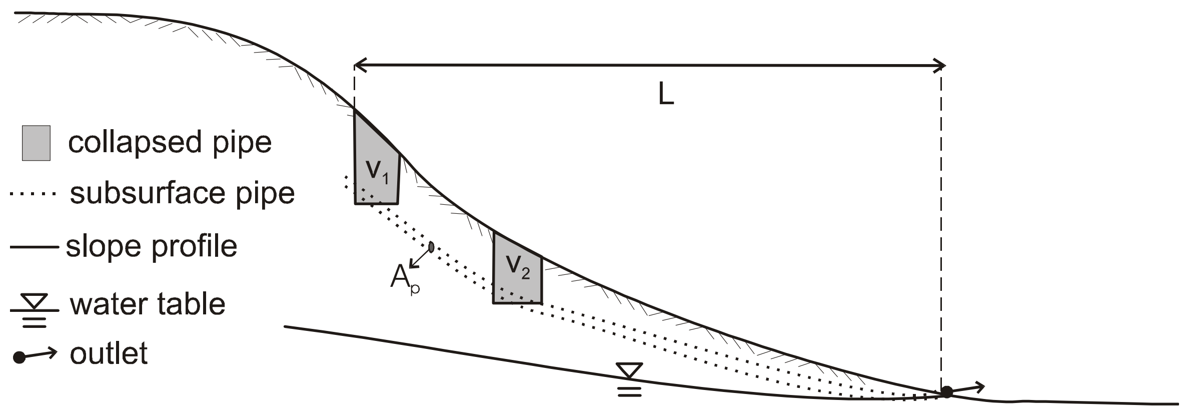


Fig. 3.4. Sketch to illustrate for the estimation of soil loss due to piping with *L* = slope length from most upslope sinkhole to the outlet (if visible), end of parcel or river; V_i = volume of the *i* the sinkhole; A_p = mean pipe cross-section.

The length *L* was calculated as the length between the most upslope situated collapsed pipe and the pipe outlet by connecting the CP in between and taking into account eventual branches of the pipe network, according to our knowledge of the field situation. The pipe outlet could be in a river or earth bank, or a place downslope of the CP where water flowing through the pipes was exfiltrating. In some cases (n = 25), the outlet was recognized as a wet spot, often close to a drainage ditch or a river channel, where the water table intersects the topography resulting in saturated overland flow. In cases where the outlet was not detected (n = 112 parcels), the length to the downslope river or creek or to the lower border of the parcel was taken. We assumed concentrated flow up on a detectable outlet or the downslope river/creek. If a parcel border was crossed before reaching the waterway, this was taken as the end point of the pipe because outlets were observed in small linchets at parcel borders as well.”The value of mean cross section A_p was based on 20 sites in

9 parcels where the pipe depth (d) and tunnel bottom width (w) were measured (Table 3.1). The pipe cross-section of the pipe was best described by a semicircle (Fig. 3.5a). Jones and Connelly (2002) reported different pipe cross sections, including the observed form of a semicircle with a flat bottom.

The volumes of the CP (n = 300) were calculated as cylindrical volumes (Fig. 3.5b). For the closed depressions (n = 195), the volume of a segment of a sphere was used (Fig. 3.5c) with w_{mean} the mean pipe width, r half the diameter of the depression and D the central depth of the depression. When the dimensions of the pipe collapse were not known (e.g. when already filled in by the farmers) the averaged depth and diameter were used. Based on interviews with farmers and field surveys, a conservative estimate of mean piping erosion rates was calculated for a 5-10 years period. Fig. 3.7 illustrates that pipe collapse may occur in less than two years. The subsurface volumes eroded which correspond to each group of CP in a parcel were attributed to a plot area having a width of 50 m and the length L. This resulted in a mean plot area of 0.3 ha, ranging between 0.02 and 4 ha.

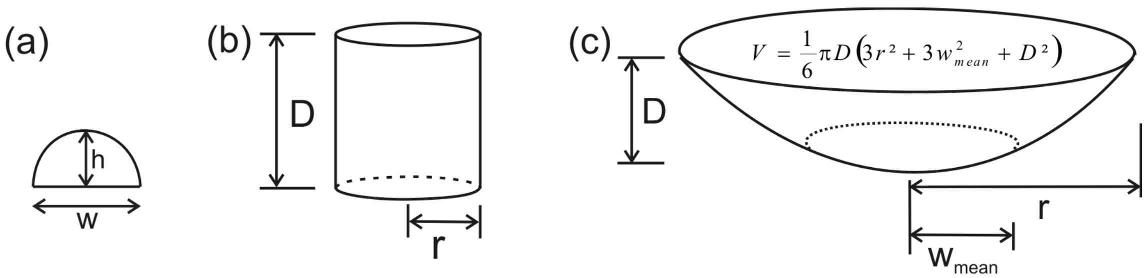


Fig. 3.5. (a) Vertical cross-section of a typical pipe (Fig. 1) with *w* the pipe bottom width and *h* the pipe height; (b) Volume estimation of a sinkhole and (c) closed depression with w_{mean} the mean pipe width, *r* being half the diameter of the sinkhole/depression and *D* the depth of the sinkhole or central depth of the depression.

The slope gradient (S, %) was calculated from a 2 x 2 m DEM (derived from LiDAR data, Light Detection And Ranging; DEM of Flanders, 2004) using routines available in IDRISI Taiga. The upslope contributing area (A, ha) was derived from a 10 x 10 m DEM using the spatially-distributed soil erosion and sediment delivery model, WaTEM/SEDEM (Van Oost et al., 2000; Verstraeten et al., 2002). S and A were calculated for both the most upslope and most downslope collapsed pipe of each parcel, as well as an average value of each parcel.

3.3. RESULTS

3.3.1. Detection and morphological characteristics

The number of parcels with collapsed pipes (CP) observed by analyzing the aerial photographs (n = 42) corresponds to one third of all parcels found during the field survey (n = 137). Many sites with CP were not visible on the orthophotos, due to their small size, because they were obscured by filling material when aerial photos were taken or because they were obscured by shadow of trees or other obstacles. A classification of piping features was made based on their morphological characteristics (Fig. 3.6). In total, 560 CP were mapped (Fig. 3.3), of which 300 were classified as sinkholes (type 1), 195 as closed depressions (type 2) and 65 as CP that were filled (type 3) by the farmer with, for example, rock and brick fragments and soil. Besides the 560 CP, three features were mapped, i.e. the pipe inlet (type 4, n = 7), pipe outlet (type 5, n = 21) and piping on earth and river banks (type 6, n = 7). CP were mapped as sinkholes when the surface (mostly grass-covered) was clearly interrupted by more or less vertical walls, while in the case of a closed depression the soil surface smoothly lowered without an abrupt change in the vegetation cover. In some cases, soil between single sinkholes collapses too, forming discontinuous gullies (type 1B, multiple sinkholes). The original morphology of filled-up sinkholes and closed depressions (type 3) is unknown, but it could be assumed that farmers mainly fill up type 1 sinkholes. The mapping of pipe inlet and outlet was based on field observations. A spot upslope of CP where water (e.g. from a spring) infiltrated into a macropore in the soil was considered as an inlet. The outlets were defined as spots where water flowing through the pipes was exfiltrating downslope of the CP. In most cases, the outlet was recognized as a wet spot, often close to a drainage ditch or a river channel, where the water table intersects with the topography resulting in saturated overland flow.

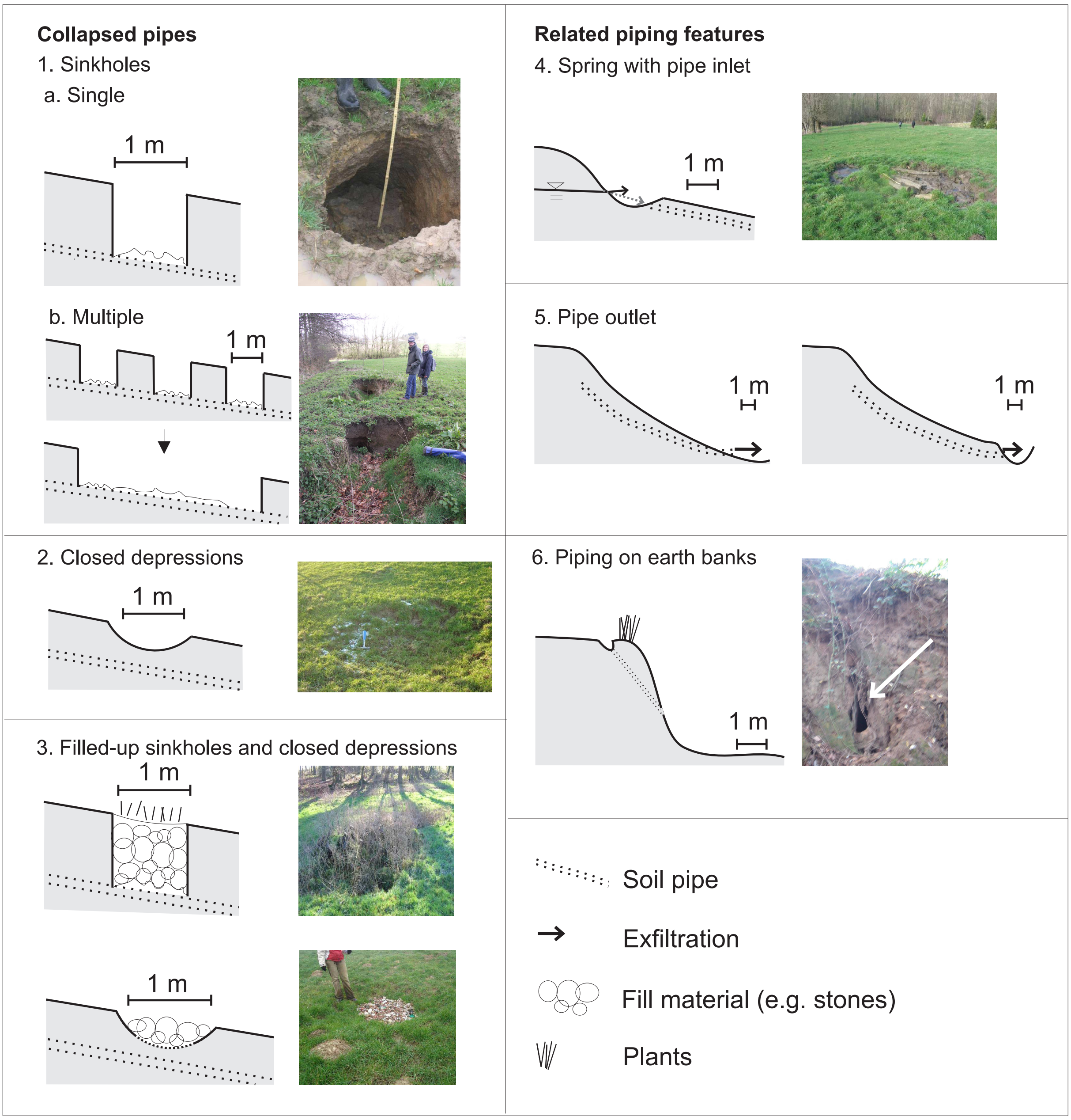


Fig. 3.6. Classification of collapsed pipes and related piping features.

Table 3.1 summarizes the morphological characteristics of the CP in the present study. Sinkholes and closed depressions have an average depth of 0.6 m and 0.3 m respectively and an average diameter of 1.1 m and 1.3 m respectively, but there is a large variation in the measured data. Where the pipe was visible, it was situated around 0.9 m below the soil surface, had a mean diameter of 0.2 m and a mean cross-section of 0.03 m²

Table 3.1. Morphological characteristics of the studied collapsed pipes and parcel characteristics.

	Sinkholes		Closed depressions		Pipe				Parcel characteristics	
	depth (m)	diameter (m)	depth (m)	diameter (m)	depth [(1)] (m)	h (m)	w (m)	A_p m²	S (%)	A (ha)
n	220	222	131	130	15	24	20	20	139	139
mean	0.57	1.13	0.29	1.34	0.93	0.17	0.19	0.030	12.9	0.881
st dev	±0.32	±0.76	±0.13	±0.82	±0.25	±0.09	±0.09	±0.008	±4.9	±1.280
mode	0.40	1.00	0.30	1.00	0.70	0.10	0.12	0.011	12.1	0.308
median	0.50	1.00	0.30	1.20	0.85	0.16	0.20	0.028	9.3	0.084
minimum [(2)]	0.20	0.10	0.10	0.20	0.70	0.06	0.05	0.003	0.8	0.042
maximum [(2)]	2.00	4.50	0.80	5.50	1.44	0.40	0.38	0.154	24.4	6.472

h = height of the pipe; w = base width of the pipe; A_p = cross-section; S = slope gradient; A = contributing area; st dev=standard deviation.
[(1)] depth of pipe base; [(2)] minimum and maximum: depths and diameters are not from the same sinkholes, depressions or pipes, not even from the same parcel.

3.3.2. Soil loss estimate

From a survey of 137 parcels with CP, a conservative estimate of soil loss due to piping was made based on the dimensions of the CP (Table 3.2). Mean soil loss due to piping was 23 $t.ha^{-1}$ for the area affected by CP, corresponding to 4.6 to 2.3 $t.ha.yr^{-1}$ at plot scale and 1.6-0.5 $t.ha.yr^{-1}$ for all pastures with CP (assuming periods of 5 to 10 years for pipe formation, respectively). In table 2, data for three scenarios are given. The low and high scenario calculations use respectively the mean minus the standard deviation and mean plus the standard deviation for the depth and diameter of the CP (used to calculate the collapses that are not visible any more) and for the tunnel cross-section. Soil loss calculations are scale-dependent. To allow a comparison at different scales, Table 3.2b also presents the subsurface soil loss rate (SSLR) for all pastures within the study area having slope gradients > 4%. This overview indicates that soil loss due to piping is small at the regional scale, while locally, it can cause high soil losses. Fig. 3.7 shows the collapse of a typical pipe during the period between December 2009 and March 2011. The soil surface area which collapsed (roof collapse) increased from 0.063 m² to 1.27 m² in 15 months.

An attempt was made to link the obtained eroded volumes of each parcel (V, m³; Eq. 3.1) with the environmental parameters such as S, A and a measure of the subsurface flow intensity expressed by A multiplied by S (A*S). The obtained subsurface erosion rates were compared to the slope gradient (S) and upslope contributing area (A) to analyse whether these factors influenced the volume lost by piping. No significant relation was found between V of each parcel and the corresponding S or A, neither calculated at the most upslope nor the most downslope collapsed pipe of the specific parcel. The parcels where only one collapsed pipe was observed were analysed separately, with the same result.

Table 3.2. Estimation of the soil loss volume and erosion rate due to piping in the 236 km² study area.

(a)	V_p	V_{cp}	V_{tot}		***SSL* (plot scale)**	***SSLR* (plot scale)**
	(m³)	(m³)	(m³)	(ton)	(t ha^{-1})	(t ha^{-1} yr^{-1})
mean scenario	253	368	621	932	23	2.3 - 4.6
low scenario	206	255	462	693	17	1.7 – 3.4
high scenario	300	725	1025	1537	38	3.8 – 7.7

(b)	all pastures with CP	all pastures with slopes > 4%
area (ha)	162	3203
mean scenario SSLR (t ha^{-1}yr^{-1})	0.6 - 1.2	0.03 - 0.06

V_p = volume pipes; V_{cp} = volume collapsed pipes; V_{tot} = total volume; *SSL* = subsurface soil loss; *SSLR* = subsurface soil loss rate for 5-10 year in the Flemish Ardennes.
Mean/low/high scenario: mean/minimum/maximum dimensions shown in Table 3.1 were respectively used for the dimensions of filled sinkholes.

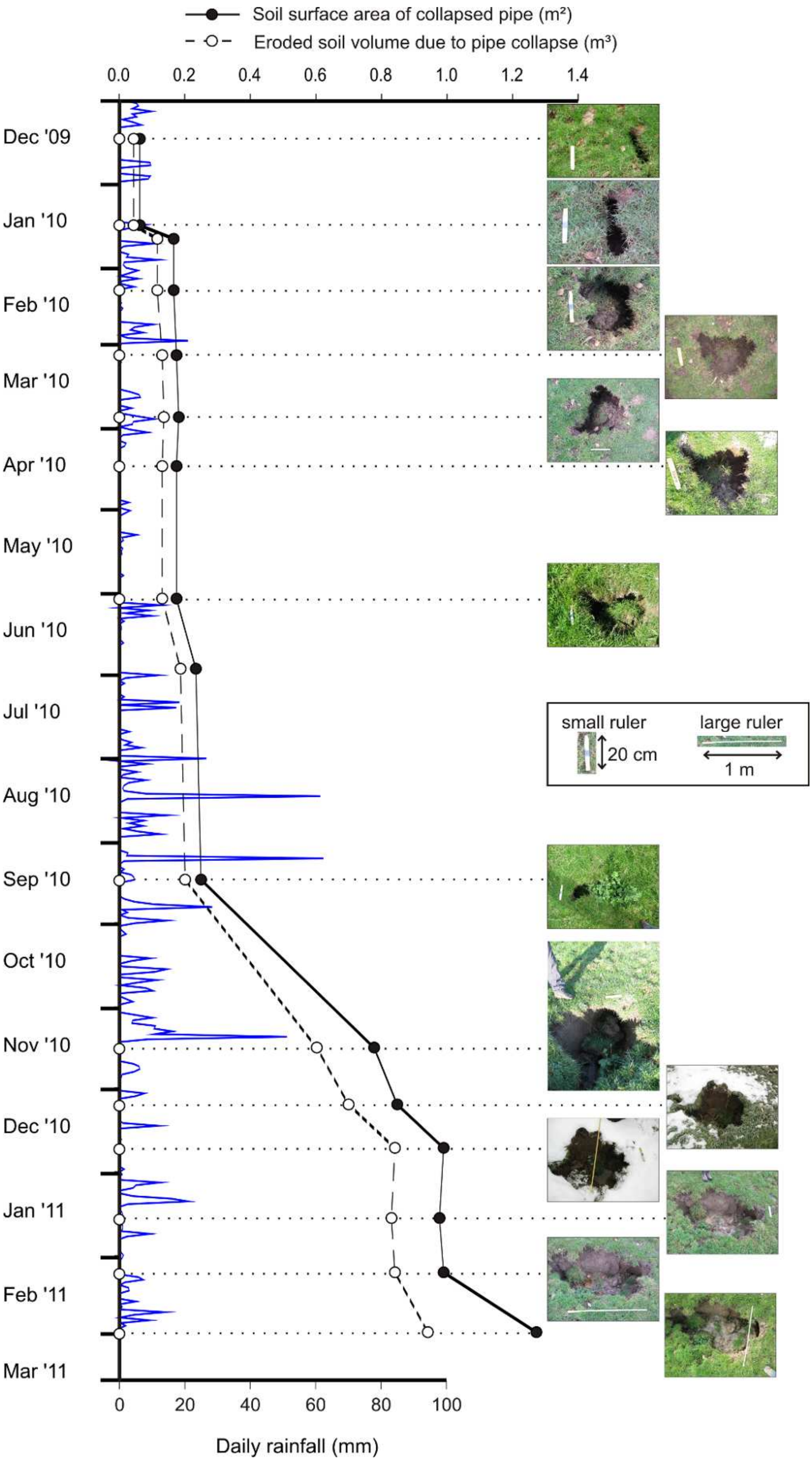


Fig. 3.7. Illustration of the evolution of pipe collapse from December 2009 until March 2011 (location: Kluisbergen) and daily precipitation recorded at the study site.

3.4. DISCUSSION

3.4.1. Quantification of soil loss due to piping erosion

In clear contrast to surface erosion, most parcels with piping erosion were observed under pasture. The pastures in the study area are already preferentially located on steeper and/or wetter slopes, 25% with a clay-rich substrate at shallow depths (in general 5-10 m, but locally within 1 m) below the loess cover (see Chapter 4). Furthermore, the presence of intense biological activity under this land use may also facilitate the vertical (earthworms) and lateral (moles) movement of water (see Chapter 7). The conservative assessment of soil loss due to piping erosion reveals a value of 2.3 - 4.6 t ha^{-1} yr^{-1} at plot scale, which is more than one order of magnitude larger than the mean soil loss rates by sheet and rill erosion for grassland in Europe (excluding the Mediterranean zone): i.e. 0.01 t ha^{-1} yr^{-1} (Cerdan et al., 2006) – 0.29 t ha^{-1} yr^{-1} (Cerdan et al., 2010). For comparison, predicted surface soil loss rate (sheet and rill erosion) is estimated at 11.4 t ha^{-1} yr^{-1} for arable land in the study area based on calculation from the Potential Erosion Map 2011 (Flemish Government, 2011; Table 3.3). If the pastures with CP would be converted into arable land, this would result in a predicted surface water erosion of 41.2 t ha^{-1} yr^{-1} according to the Potential Erosion Map 2011. It should be mentioned that the soil loss predictions are often overestimations as the entire study area is considered to be cropland and the effects of soil conservation measures are not taken into account. Nevertheless, conversion of pastures with CP into arable land would largely increase soil losses, compared to the soil losses due to surface and surface water erosion when pasture remains.

Table 3.3. Predicted erosion rates for cropland in the study area.

	Soil loss rates (t ha^{-1} yr^{-1})		
Land use	Surface water erosion (sheet and rill erosion)	Tillage erosion	Subsurface water erosion (piping)
Cropland in the study area	11.4 *	6.5*	/
Pastures with CP converted to cropland	41.2 *	16.5*	/
Pastures with CP	2.2 * 0.01 – 0.29 **	/	0.6 – 1.2

* predicted values according to the Potential Erosion Map 2011 (Flemish Government, 2011), calculated with a C factor of 0.02 for the pastures; ** plot data from Cerdan et al. (2006; 2010)

The calculation of the subsurface soil loss rate was based on the area of the parcels affected with CP and a 5-10 years period. This time period can be the subject for discussion, as piping in the study area only becomes visible after pipe collapse. Field observations, however, indicate that large CP can already appear after one major storm, although it is not clear how long before subsurface pipe enlargement started. Furthermore, the extent of the pipe network is not known. Because only the visible pipes (after collapse) can be included in the calculation and because the chosen length *L* reflects only a minimum pipe length, the resulting estimate represents a conservative erosion rate. The erratic character of pipe enlargement is illustrated in Fig. 3.7, showing a large increase after the major rainfall event of 12 November 2010 while the collapsed volume remained rather constant during the summer period. Pickard (1999) also pointed to the episodic expansion rates of tunnels in gypsum in Australia, after measurements of collapse holes from 1983 to 1996.

The subsurface soil loss volume of a parcel was not related to its corresponding slope gradient or drainage area. It is possible that the local hydraulic gradients and the subsurface contributing area that influence pipeflow do not necessary equal S and A, calculated at the soil surface. Nevertheless, S and A are important factors controlling the location of CP in the study area (Chapter 4 and 5) and one could expect that locations with a steep S and a large A have more intense subsurface erosion. A possible explanation why S and A are not found to influence the eroded soil volume locally may be the common practice among farmers to fill in the CP as soon as they form. Hence, repeated erosion at the location of a collapsed pipe is only once accounted for with the used method.

3.4.2. Comparison of subsurface erosion rates due to piping in different environments

Several authors reported measurements of soil loss due to piping (e.g. Barendregt and Ongley, 1977; Bryan and Harvey, 1985; Farres et al., 1990; Torri et al., 1994; Zhu et al., 2002), but the areal extent was not always reported. The few estimates of area-specific soil loss rate due to piping in various environments are summarized in Table 3.4a, other studies that reported soil loss measurements of piping for one of more (simulated) events are listed in Table 3.4b. Some studies considered gully systems caused by piping rather than net piping erosion (e.g. Poesen, 1989; Rodzik et al., 2009). Based on repeated surveys of CP in a parcel of ca. 1 ha, Botschek et al. (2000) estimated the soil loss to be about 15 t in three months during the most active period for piping in a loess area similar to the study area of this paper (although steeper slopes). If assumed that the studied site was stable during the rest of the year, the estimation of 15 t ha^{-1} yr^{-1} largely exceeds our conservative assessment. However, the parcel with the largest subsurface soil volume lost for an individual parcel in our study was estimated at 7.5 m^3 or 11 ton, coming close to the 15 ton measured in Germany. According to Kerényi (1994), the subsurface erosion rate is four to five times more intense than surface erosion rates by water on loess terraces in Hungary. He estimated the volume of loess removed by six subsurface features to be 494 m^3 for 2 ha over a 25 year time-span. The corresponding value of 14 t ha^{-1} yr^{-1} also includes terrace bank failures which were not taken into account in our estimation. Another intensive investigation of subsurface erosion was carried out by Beckedahl (1998) in South-Africa (southern Kwazulu-Natal and Transkei), who estimated the total soil loss due to piping in the area between 1300 and 1750 tonnes. Erosion rate estimates varied from 0.7 to 14.2 t ha^{-1} yr^{-1} (including pipe related gullies) for three catchments that were studied in detail. Furthermore, ground-penetrating radar applications in peat land suggest that the length of the pipes may be more than twice that which surface mapping suggests (Holden and Burt, 2002). If this is also true for the study area in Belgium, this would increase the estimation of the eroded volume by one third (Eq. 3.1).

Piping and soil loss are more intense (2 – 20 times) in semi-arid or arid environments with badlands like the marl badlands in Spain (Romero Díaz et al., 2009: 287 t ha^{-1} yr^{-1}), Italy (Torri et al., 1994) and Canada (Barendregt and Ongley, 1977), or in other highly erodible environments like the loess plateau in China (Zhu et al., 2002; Zhu, 2003: 33 t ha^{-1} yr^{-1}), compared to temperate regions (0.7-15 t ha^{-1} yr^{-1}). Correspondingly, the various dimensions of pipe as well as collapses illustrate this difference. In badlands or semi-arid regions, the pipe diameter can exceed several meters (Barendregt and Ongley, 1977; Uchida et al., 2001; Zhu, 2003; Romero Díaz et al., 2009). Nevertheless, smaller dimensions have been reported as well in semi-arid regions. The pipes in the Biancana badlands in Italy monitored by Torri et al. (1994; Table 3.3b) are 3-4 cm in width and up to 10-15 cm in height. In semi-arid southern Australia, Pickard (1999) observed tunnels in gypsum up to 0.5 m diameter between holes up to 3 m diameter and 1.8 m deep. In temperate environments, average pipe diameters are rather 0.15 m (mid-latitude marine) and 0.25 m (mid-latitude humid continental) according to the literature review of Bryan and Jones (1997). For loess in a temperate environment, pipe diameters range from 0.05 to 0.30 m in Germany (Botschek et al., 2002b) and ca. 0.20 to 0.80 m in Hungary (Kerényi, 1994), similar to the dimensions observed in the Flemish Ardennes (i.e. a mean pipe diameter of 0.2 m). Holden and Burt (2002) observed mean pipe diameter ranging from 0.03 to 0.70 m, measured at the outlet of pipes in deep peat in the UK. Smaller dimensions (5 – 30 cm) were reported for thin peats by Jones (1982). Holden and Burt (2002) emphasize that the pipe shape, size and depth may differ significantly over small distances, which was reported as well by Terajima et al. (2000) using a fibrescope in a Japanese forested hillslope. In the Japanese forests listed in the review of Uchida et al. (2001), the diameter of pipe outlets is sometimes even smaller than 0.01 m, but varies over a wide range (i.e. 0.001–0.60 m).

3.4.3. Significance of subsurface erosion

Despite the reported wide range of subsurface erosion rates in different environments but also within one environment, the present study as well as related studies confirms that piping erosion is a significant contributor to soil loss. Even if the pipes themselves are rather small, it is clear that piping can lead to more severe soil loss by roof collapse and its interaction with gully erosion and landsliding (cascade-effect; e.g. Poesen, 1989; Poesen et al., 1996). Barendregt and Ongley (1977) reported that the sediment load of a subsurface flow is probably greater than that of a surface stream at the same location would have because of the additional sediment supplied by continued collapse. Furthermore, they concluded that the majority of the gully systems are CP in their study area (i.e. the Milk River Canyon area, Alberta badlands). Zhu (2003) observed in the loess plateau of China that the sediment yield by tunnel erosion was mainly produced by the initiation and enlargement of tunnel inlets rather than tunnel paths. In the case studied by Farres et al. (1990) in the UK, the main deposit was not derived from the pipe walls but the pipe acted as a pathway. In contrast to the transport function in other regions, the sediment produced by piping erosion in the pastures of the present study does mainly originate from enlargement of pipes and roof collapse. Both Zhu (2003) and Pickard (1999) reported that the diameters of tunnel inlets or collapsed tunnels may enlarge significantly while the changes in depth are rather limited.

Beside the soil loss itself, Beckedahl (1998) mentioned socio-economic off site implications of subsurface erosion in South-Africa as well. For instance, dispersed clays that resulted from piping erosion frequently remain in suspension for several days and can pose a problem for potable water by increasing the cost of water purification. For peatland, the production of sediment by pipes may not only be important as a geomorphological process but also as a component of peatland carbon cycles (Holden, 2006). Holden (2006) studied the growth rates of peat pipes in relation to open drainage ditches. Pipe density was increasing at a rate of 2.1 pipes (km stream bank)$^{-1}$ yr^{-1} and mean pipe diameter at a rate of 0.09 cm yr^{-1}, which resulted in an exponentially increasing cumulative volume of particulate carbon loss from the peat mass over time on drained slopes. Piping is chemically important, draining solute-rich water (Walsh and Howells, 1988). Notwithstanding the potentially significant contribution of subsurface erosion, soil erosion models do not explicitly incorporate this erosion process. The main reasons that Beckedahl (1998) gave for this are still standing: (i) limited availability of detailed input data and (ii) difficulties of obtaining reliable information on pipeflow in relation to precipitation and antecedent soil moisture content. More recently, there is an increasing number of studies that monitor pipeflow continuously (e.g. Uchida et al., 1999; Botschek et al., 2000; Zhu et al., 2002; Holden and Burt, 2002; Jones and Connelly, 2002) and attempts have been made to model pipeflow (e.g. Jones and Connelly, 2002). Nevertheless, modelling subsurface flow and especially subsurface soil loss remains a challenge in piping research.

3.4.4. Quantification of subsurface soil loss using artificial subsurface drains

As quantitative assessments of soil loss trough piping erosion are limited, a literature review of soil loss through drainage pipes is included to further illustrate the geomorphological significance of subsurface erosion through preferential channels.

Few studies have specifically aimed at quantifying soil loss through drains (e.g. Øygarden et al., 1997; Turtola et al., 2007; Warsta et al., 2009; Table 3.4). Most research has concentrated on drainage water quality (i.e. pesticide, phosphorus, nitrogen and other nutrient losses) through artificial drainage systems. However, some of these studies also report total suspended sediment yield in combination with the total surface soil loss through interrill and rill erosion. Direct measurements of sediment yield (Table 3.5) from drainage systems show that subsurface sediment yield ranges between 0.05 and 2.94 t ha^{-1} yr^{-1}, with an average of 0.59 t ha^{-1} yr^{-1}. Sediment yield from drains amounts to between 12% and 912% of surface sediment yield, with an average value of 116%. Hence, sediment yield from drains can be a significant and even the main contributor to total sediment yield.

Significant subsurface soil losses through artificial drains were reported in runoff plot studies in cold climates in Norway, Finland, Sweden and Canada. The experiments were conducted on clayey soils, which were drained and sometimes also artificially levelled (Øygarden et al., 1997; Lundekvam, 2007) for cropland farming. In one of the only studies specifically aimed at quantifying soil loss through drainage networks, Øygarden et al. (1997) found that soil loss through drainage water decreased from 3 t ha^{-1} yr^{-1} the first year after drain installation to 0.12 t ha^{-1} yr^{-1} in the sixth year, resulting in an average value of 1.3 t ha^{-1} yr^{-1} over the six year monitoring period. Culley and Bolton (1983) estimated 18% of suspended solids to be derived from subsurface drainage in a catchment mainly composed of clayey soils in Ottawa, Canada.

The significance of soil loss through drainage pipes in environments other than cold-climate clayey soils was demonstrated by Sogon et al. (1999) who registered sediment exports up to 0.24 t ha^{-1} yr^{-1} in a drained agricultural catchment (6.4 ha) in the Brie region (France). Here, they found that sediment delivered through the drainage system mainly consisted of fine soil particles from the plough layer and suggested that high annual river sediment yield of drained catchments in wet years is likely due to the erosion of sediment stored in drainage networks during dry years. Furthermore, Grazhdani et al. (1996) found that soil loss through drains constituted 13-19% of total soil loss (by sheet, rill and drainage erosion) on Chernozems in a Mediterranean climate (Albania).

Table 3.4. Estimates of mean area-specific soil loss rates due to piping (a) and event-based soil losses due to piping (b).

(a) Location	Soil/lithology	*annual P* (mm)	*StA* (ha)	*P* (yr)	*SSLR* (t ha^{-1}yr^{-1})	*ratio*	*d* (m)	Type of measurement	Source
Germany (Bonn)	silt loam (loess)	1045	1	0.25	15	n.a.	0.05-0.30	volumetric	Botschek et al., 2000; 2002
Hungary (Tokai)	silt loam (loess)	624*	2	25	14.3	4 - 5	0.20-0.80	volumetric	Kerényi, 1994
South-Africa	sandy loam - clay	800-1250	0.15-25 (drainage area)	n.a.	0.7 - 14.2	n.a.	0.3-1.3 (w) 0.3-1.2 (h)	volumetric	Beckedahl, 1998
Spain (Murcia)	marls (badlands)	212*	16.6	40	287	n.a.		volumetric	Romero Diaz et al., 2009
Belgium	Luvisol (loess)	700-850	126	5 - 10	1.5 - 3	n.a.	ca. 0.05-0.20	volumetric	Poesen et al., 1996
			100	5 - 10	1.2 - 2.4	n.a.		volumetric	
South-Africa	Histic Gleysol	1050	4.2	0.25	0.005	n.a.	ca. 0.88	weekly sediment yield (filter)	Garland and Humphrey, 1992
Poland	silt loam (loess)	600	123	4	0.96**	3.7	ca. 0.2-1.0	sediment yield + volume sediment accumulation	Rodzik et al., 2009
China (Yangdaogou)	silt loam (loess)	497	20.6	12	33	0.4	1.43-6.64	volumetric	Zhu, 2003

(b) Location	Soil/litholoy	*annual P* (mm)	*StA* (ha)	*P* (yr)	*SSL* (ton)	*flux* (g s^{-1})	*load* (g l^{-1})	*d* (m)	Type of measurement	Source
UK	Eutric Gleysol Gleyic Cambisol	697*	n.a.	one event	0.063	n.a.	n.a.	0.05	volume sediment accumulation	Farres et al., 1990
Canada (Alberta)	marls (badlands)	330	n.a.	one event	112	n.a.	n.a.	up to several meters	volumetric	Barendregt and Ongley, 1977
Italy (Tuscany)	marls (badlands)	645	15	rainfall experiment of 14 min + 9 min	n.a.	3.3	1.3 10^{-4}	0.03-0.04 (w) 0.10-0.15 (h)	sediment yield	Torri et al., 1994
					n.a.	0.8	1.3 10^{-4}			
					n.a.	0.9	1.3 10^{-4}			
Canada (Alberta)	marls (badlands)	325	n.a.	3 storms	5.14 - 37.13 10^{-3}			0.007-2.94	sediment yield	Bryan and Harvey, 1985
				3 storms	25.76 - 85.05 10^{-3}					
China	silt loam (loess)	500 (334.9)	22	1	n.a.	n.a.	8.2-893.2	4.8	sediment yield	Zhu et al., 2002
Germany	silt loam (loess)	1045	1	1 month		0.005-2.1	0.3-25.6	0.05-0.30	sediment yield	Botschek et al., 2000; 2002

StA = size of study area (ha); P = measuring period; SSLR = subsurface soil loss rate; ratio = subsurface soil loss/surface soil loss by water erosion; d = (mean) pipe diameter; (w) = pipe base width and (h) = pipe height; annual P = long-term mean annual precipitation; SSL = subsurface soil loss; flux = sediment flux; load = sediment load; n.a. = not available. * annual P not reported by authors, but derived from NewLocClim (FAO, 2005) for the study site; ** the material originates from piping-headcut wells and potholes as well as piping tunnels; n.a. = not available.

Table 3.5. Subsurface soil loss measured at artificial drain outlets.

Location	Soil/litholoy	Land use	*StA* (ha)	*P* (yr)	*SSLR* (t ha^{-1} yr^{-1})	*ratio*	Type of measurement	Source
Norway (Askim)	artificially levelled silty clay loams with low humus content	cropland [(a)], autumn tillage	0.017 and 0.031	7	0.95	0.20	sediment yield (runoff plot)	Lundekvam and Skøien, 1998; Lundekvam, 2007
		cropland [(a)], spring harrowing	0.017 and 0.031	7	0.95	1.89		
Norway (Syverud)	silty clay loam with high humus content	cropland [(a)], no-tillage in autumn	0.0196	7	0.12	0.78	sediment yield (runoff plot)	
		cropland [(a)], autumn tillage	0.0196	7	0.05	0.46		
Norway (Ullensaker)	levelled silty clay loam	cropland [(a)], autumn tillage	0.90	3	2.40	1.56	sediment yield (catchment)	Øygarden, 1997
		cropland [(a)], no-tillage	0.90	1	0.31	0.12		
		meadow	0.90	2	0.23	0.60		
Finland (Jokioinen)	Cambisol	cropland [(b)]	0.44	5	0.65	0.44	sediment yield (runoff plot)	Turtula and Paajanen, 1995
		cropland [(b)]	0.44	5	0.41	0.28		
		cropland [(c)]	0.44	5	0.34	0.29		
		cropland [(c)]	0.44	5	0.37	0.28		
Finland (Jokioinen)	Cambisol	cropland and grass ley [(d)]	0.44	2	1.07	3.48	sediment yield (runoff plot)	Turtola et al., 2007
		cropland [(a)], autumn tillage	0.44	3	0.60	1.85		
		cropland [(a)], no-tillage	0.44	3	0.53	2.30		
		cropland [(a)], autumn tillage	0.44	5	1.11	9.12		
		cropland [(a)], shallow stubble	0.44	5	0.74	1.57		
Finland (Sjökulla)	Gleyic Cambisol	cropland [(a)]	3.3	1	2.94	1.10	sediment yield (catchment)	Warsta et al., 2009
		cropland [(a)]	3.3	1	1.28	0.54		
France (Brie region)	clayey and silty soils	cropland	6.43	3	0.13	n.a.	sediment yield (catchment)	Sogon et al., 1999; Penven et al., 2000
Sweden (Oxelby)	Eutric Cambisol	cropland [(b)]	4.43	6	0.13	n.a.	sediment yield (catchment)	Ulén and Persson, 1999
		cropland [(b)]	4.43	6	0.08	n.a.		
Albania (Lumalas)	Calcic Chernozem	cropland [(e)]	0.06	5	0.22	0.13	sediment yield (runoff plot)	Grazhdani et al., 1996
		cropland [(e)]	0.06	5	0.24	0.12		
		cropland [(e)]	0.06	5	0.24	0.19		
Albania (Drithas)	Calcic Chernozem	cropland [(e)]	0.06	5	0.20	0.13	sediment yield (runoff plot)	
		cropland [(e)]	0.06	5	0.22	0.12		
		cropland [(e)]	0.06	5	0.22	0.19		
Canada (Ottawa)	clay soil	cropland [(e)]	n.a.	2	0.41	n.a.	n.a.	Culley and Bolton, 1983
		permanent grassland	n.a.	2	0.10	n.a.		

StA = size of study area (ha); *P* = measuring period; *SSLR* = subsurface soil loss rate; *ratio* = subsurface soil loss/surface soil loss by water erosion;
[(a)] cereal cultivation; [(b)] cereal and fallow rotation; [(c)] cereal and grass rotation; [(d)] cereals undersown with clover and timothy, followed by grass ley; [(e)] silage maize cultivation.

Alternatively, tracer element studies allow to discriminate between sediment from subsurface (i.e. drainage) or surface (i.e. interrill and rill erosion) sources. Soil loss from land drains in 2 agricultural catchments in the United Kingdom were estimated by Russell et al. (2001) and Foster et al. (2003) using the ^{210}Pb and ^{137}Cs tracer methods. They found soil loss through land drains between 0.07 and 0.98 t ha^{-1} yr^{-1}, constituting between 25.4 and 55.3% of the total suspended sediment load. Using similar techniques, Kronvang et al. (1997) found soil loss through subsurface drainage water to be 13% of total soil loss in the Gaelbek stream Denmark. Pilgrim and Huff (1983) measured sediment concentrations as high as 1 g l^{-1} in subsurface flow through a silt loam soil on a 17° slope under grass in California in storms of 10 mm h^{-1} intensity or less, using tracer techniques as well.

Despite differences in dominant land use and experimental methods, both soil loss through piping and soil loss trough drainage pipes constitute a significant part of total soil loss in all studies, which illustrates the importance of erosion associated with subsurface flow. Furthermore, since pipes are bound to expand and eventually collapse, their potential for causing significant gully erosion is even higher than for drainage pipes.

3.5. CONCLUSIONS

This study resulted in a regional inventory of CP, unique for the European loess belt. Although analysis of orthophotos can help to detect CP, detailed field surveys are necessary. It remains difficult to precisely quantify subsurface soil loss due to piping erosion because of the large complexity of the pipe network, the temporal variations in pipeflow and, of course, the fact that the dimensions of the pipes are only locally revealed after collapse. The conservative estimation of soil loss obtained in this study reveals that piping erosion can locally cause surprisingly high soil loss for a highly-vegetated land use (pasture) in a temperate humid climate that is traditionally considered to be a land use without significant erosion problems. Despite the large variations in the soil loss estimates, it can be concluded from the present study as well as from literature that piping erosion is a significant contributor to soil loss. Especially for grassland, piping is the dominant erosion process. The high subsurface soil losses are caused by the creation of sinkholes and roof collapses rather than by erosion of the pipe walls between the CP. Furthermore, subsurface erosion may be increased by the interaction with other erosion processes such as gully erosion and landsliding. These interactions were not included in the present estimate and will be the subject of future research. Given its significance, subsurface erosion needs to be considered as well when assessing overall soil losses for a given region with soil types and topography susceptible to piping.

Chapter 4

Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: a case study from central Belgium *

4.1. INTRODUCTION

Most research on piping in Europe was performed on organic-rich soils in the United Kingdom (e.g. Jones et al., 1997; Holden and Burt, 2002) and dispersive material in the Mediterranean area (e.g. García Ruiz et al., 1986; Torri and Bryan, 1997; Farifteh and Soeters, 1999), while limited information exists about piping in loess-derived soils in temperate climate. However, observations made in Belgium (Poesen, 1989), Germany (Hardenbicker, 1998; Botschek et al., 2002a; 2002b) and Hungary (Kerényi, 1994) reveal the importance of piping in this context. Early literature reports about piping in loess-derived soils in Poland (e.g. Malicki, 1935; Czeppe, 1960; Malinowski, 1963). In semi-arid climate, however, the susceptibility of loess for piping is well known in northern China (e.g. Zhu et al., 2002; Zhu, 2003) and New Zealand (e.g. Hughes, 1972). For loess in Germany, Botschek et al. (2002b) reported that there was no relationship between the chemical soil properties and the vulnerability to piping. This is in clear contrast to piping in the Xerosols of the Mediterranean area, where clay dispersion plays a significant role (Faulkner, 2006). Unlike extensive knowledge on sheet and rill erosion and gullying in loess (e.g. Poesen, 1993; Nachtergaele et al., 2001; Vanwalleghem et al., 2005), less is known about the topographical and soil properties triggering pipe development in the collapsible soils of the Northern European Belt under a temperate climate. Therefore, this research aims at a better understanding of the main factors controlling piping in the loess-derived soils in Belgium. More specific objectives for the selected study area in the Flemish Ardennes are: (1) to map the spatial distribution of collapsed pipes, (2) to link the occurrence of collapsed pipes to the environmental characteristics, and (3) to compare the topographical thresholds controlling the occurrence of piping to gullies

* based on: Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2010. Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: a case study from central Belgium. Geomorphology 118: 339-348.

and landslides. To obtain these insights, an extensive regional inventory of collapsed pipes was carried out, unique in loess-derived soils in temperate climate.

4.2. MATERIAL AND METHODS

In total, 137 parcels having 560 CP were mapped with GPS (Trimble 2005 GeoXT; accuracy <1m; Fig. 4.1). The surveys and classification of the CP are described in Chapter 3. Topographical variables such as hillslope gradient, aspect, distance to the thalweg, profile and plan curvature were derived from LiDAR data (Light Detection And Ranging; DEM of Flanders, 2004) using routines available in IDRISI Andes and ArcGIS™. More information about the LiDAR data used can be found in Van Den Eeckhaut et al. (2007b). The local slope gradient of the soil surface was also measured with a clinometer at the most upslope and most downslope collapsed pipe location within every parcel. Information on lithology and soil was derived from the Tertiary geological map (1:50,000; AGIV, 2001a) and the soil map (1:20,000; AGIV, 2001b) respectively, both converted to raster data with a 10×10 m resolution. The Belgian soil map gives a class for soil texture, soil drainage and soil profile development. The original drainage classes from the soil map were grouped into 3 classes (dry, wet, very wet) for further analysis. For each pixel, the upslope contributing area (A; ha) was calculated using routines from the spatially distributed soil erosion and sediment delivery model, WaTEM/SEDEM. Detailed descriptions of the model are provided in Van Oost et al. (2000) and Verstraeten et al. (2002). The parcels in the study area with pasture and arable land were determined from a land use map (1:10,000; AGIV, 2004).

The relationship between slope gradient (*S*, m m^{-1}) at a collapsed pipe site and corresponding drainage area (*A*, ha) was investigated using the negative power relationship earlier derived for gully initiation (e.g. Abrahams, 1980; Moore et al., 1988; Montgomery and Dietrich, 1994; Vandekerckhove et al., 2000; Poesen et al., 2003; Vanwalleghem et al., 2005):

$$S = \mathrm{a}\ A^{-\mathrm{b}} \tag{4.1}$$

with a and b coefficients. This relationship was determined by ordinary least squares regression on double logarithmic scale. In order to obtain the topographical threshold line, a straight line was fitted through the lowermost of the data points, with a slope equal to the slope of the regression line.

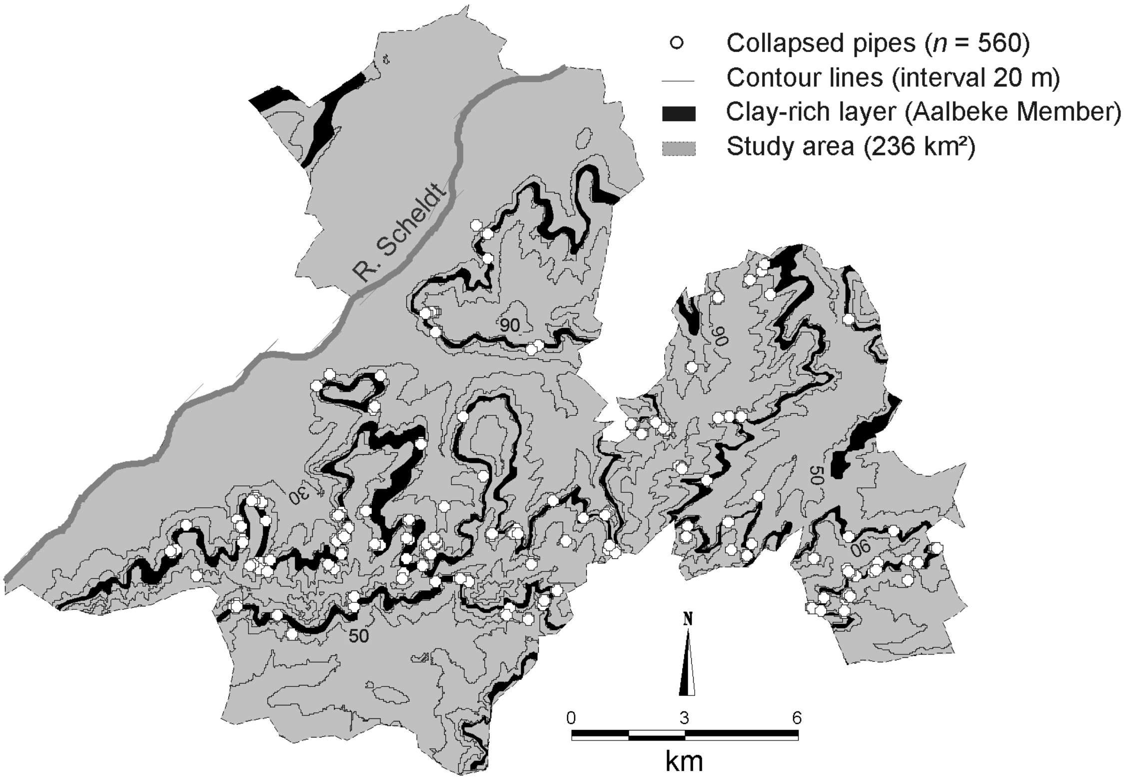


Fig. 4.1. Location of the study area in Belgium and inventory of the collapsed pipes (*n* = 560) projected on a map with indication of the clay-rich Aalbeke Member (Tertiary lithology).

4.3. RESULTS

4.3.1. Spatial distribution of collapsed pipes and environmental factors

In terms of spatial distribution, 97% of the parcels with CP are located in a pasture, while only 3% and 1% are located in arable land or in forest, respectively (Fig. 4.2). The available land use map was used to classify the land use of the study area and to select the pastures of the study area, but the land use of the parcels with piping was classified based on field observations because these observations were more accurate. Fig. 4.3 shows histograms of environmental factors which may influence the spatial occurrence of CP in the study area. Due to the grid cell resolution of 10×10 m, the analysis was made based on 417 grid cells enclosing 1 or more CP (n = 560) and 2.3 x 10^6 grid cells comprising the entire study area. The CP are predominantly located on the hillslopes and less in the valley-bottoms or on the plateaus (Fig. 4.1 and 4.3a). In the study area, piping occurs on slopes between 2% and 31%, with a sharp increase in the frequency of piping on slopes with gradients exceeding 8%. Note that the slope gradient in this figure is calculated from the LiDAR-derived DEM. Slopes facing west, and to a lesser extent east, are most favourable for piping (Fig. 4.3b). As expected, more piping occurs on hillslopes with plan and profile concavities compared to straight or convex hillslopes (Fig. 4.3c,d) and 49% of the CP are located on a distance less than 15 m from the thalweg. The frequency distribution of slope, aspect and curvature for the pastures in the study area is quite similar to that for the whole study area.

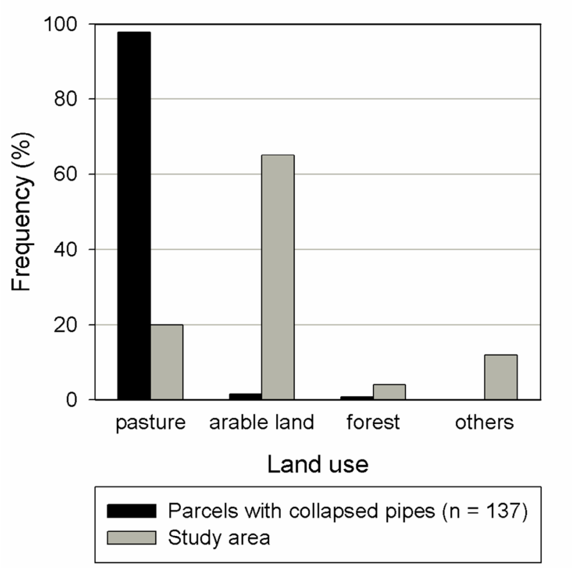


Fig. 4.2. Frequency distribution of land use classes for parcels with piping and that for the whole study area.

Concerning lithology, most prone to piping are the areas with the Aalbeke Member (> 50% smectite clay) under the shallow loess cover. More than 28% of the sites with piping are located on this lithological layer, while this layer covers only 8% of the study area (Fig. 4.3e). The rest of the CP are mainly located on the Tielt Formation and Moen Member. These two lithological layers contain clay as well as silt and sand, and cover a large part of the study area. The pastures of the study area are preferentially located on the Saint-Maur Member (valleys) and Aalbeke Member. Soil texture, soil drainage class and soil profile development seem to be of less importance (Fig. 4.3f,g,h). The texture of the soils with piping ranges from silty-clay loam to sandy loam. Very wet soils are preferred above wet or dry soils (% CP compared to all pastures), and there is a higher frequency of piping on soils with no profile development. In general, the pastures follow a similar soil pattern as the total study area, although there is a slightly higher frequency of pastures on wet soils and soils without profile development.

4.3.2. Topographical threshold for piping

The slope–drainage area relation for piping in the study area (Fig. 4.4 and Fig. 4.5) shows a significant negative trend of the form of Eq. 4.1. In order to determine the topographical threshold, a straight line was fitted through the lowermost of the data points, with a slope equal to the slope of the regression line. The points under the threshold line were considered as outliers because S and/or A were known to be artificially changed. The following topographical threshold equations were obtained:

$$S_{\mathrm{DEM}} = 0.017\ A^{-0.123} \quad (R^2 = 0.16;\ n = 417) \qquad (4.2)$$

with S_{DEM} the slope gradient calculated from LiDAR-derived DEM;

$$S_{\mathrm{field}} = 0.019\ A^{-0.140} \quad (R^2 = 0.15;\ n = 196) \qquad (4.3)$$

with S_{field} the slope gradient measured in the field. S_{field} was measured only for the most upslope and most downslope collapsed pipe of each parcel (n = 196). The slope gradients of these 196 CP were used for calibrating Eq. 4.3. A significant correlation was found between S_{DEM} and S_{field} (R^2 = 0.63; $p < 0.05$), justifying the further use of S_{DEM}. A subdivision of the CP according to their position along the hillslope (most upslope vs. most downslope) did not result in significantly distinct *SA* threshold equations.

These two thresholds define the lowermost conditions below which no pipe collapse is expected. An additional moderate threshold was defined allowing 5.5% of the CP data below the threshold, being a useful tool for predictions (see also section 5.2.4).

$$S_{DEM} = 0.07A^{-0.123} \qquad (4.4)$$

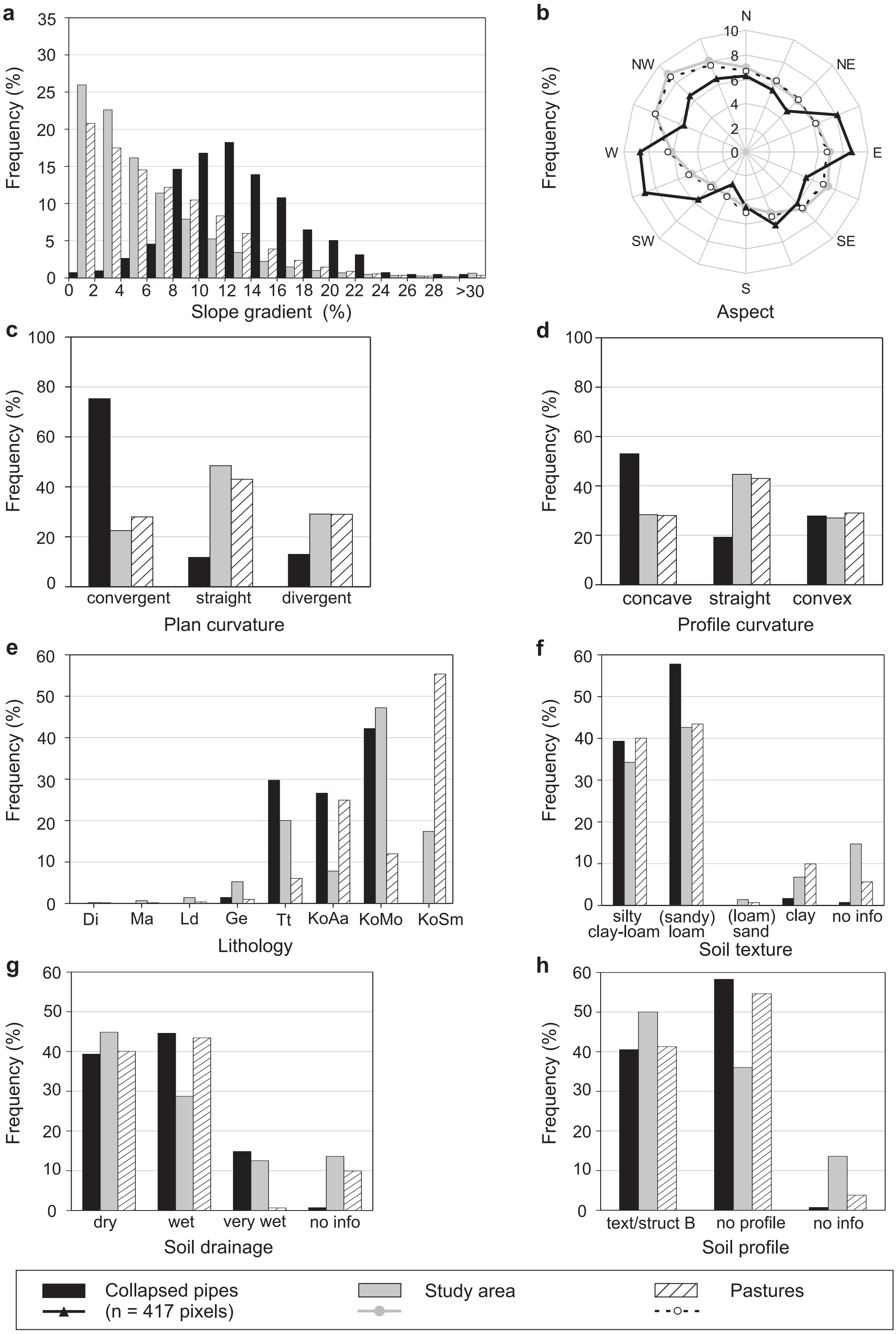


Fig. 4.3. Frequency analysis of environmental parameters for the mapped collapsed pipes, the whole study area and the whole pastures of the study area. (a) Slope gradient. (b) Aspect [N: north, E: east, S: south, W: west]. (c) Plan curvature. (d) Plan curvature. (e) Lithology [Di (Diest): glauconitic sand, Ma (Maldegem): clay and glauconitic sandy clay, Ld (Lede): sand; Ge (Gent): glauconitic sand and clay with sand lenses, Tt (Tielt): glauconitic clayey sand, with clay and lithified sand layers; KoAa (Aalbeke): homogeneous blue massive clay; KoMo (Moen): clayey silt to sand with clay layers; KoSm (Saint-Maur): silty clay]. (f) Soil texture. (g) Soil drainage. (h) Soil profile development [text/struct B: texture or structure B horizon, no profile: without profile development].

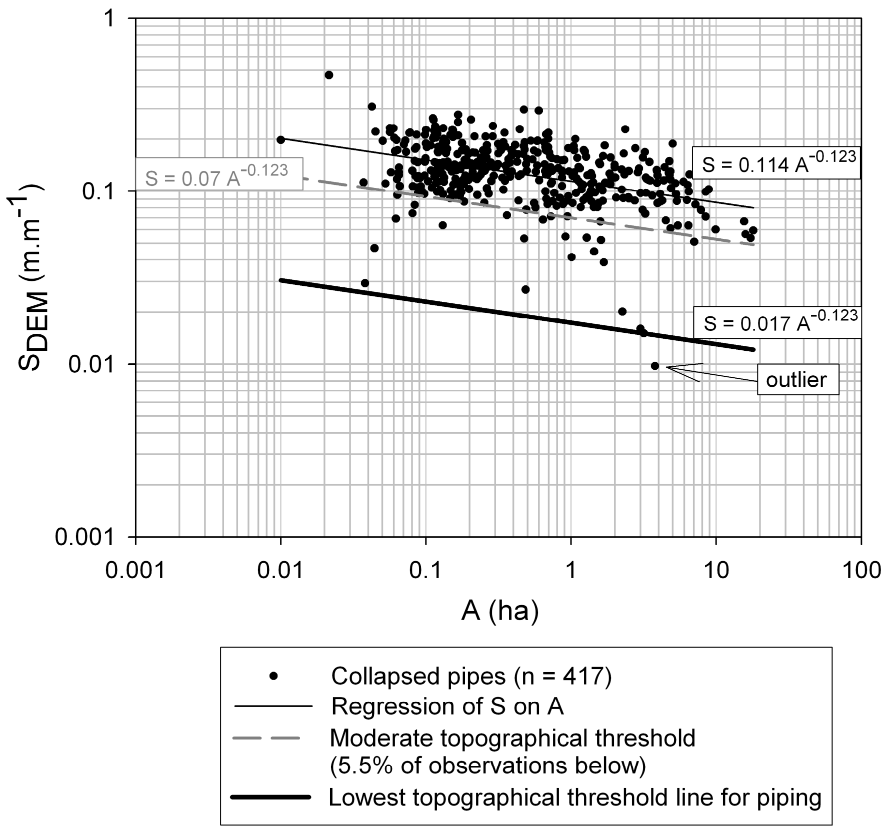


Fig. 4.4. Relation between drainage area (*A*) versus soil surface slope gradient (S_{DEM}), both calculated from the LiDAR-derived DEM, with indication of two topographical threshold lines for pipe collapse: one moderate threshold allowing 5.5% of the observations below and one threshold below which no pipe collapse is expected.

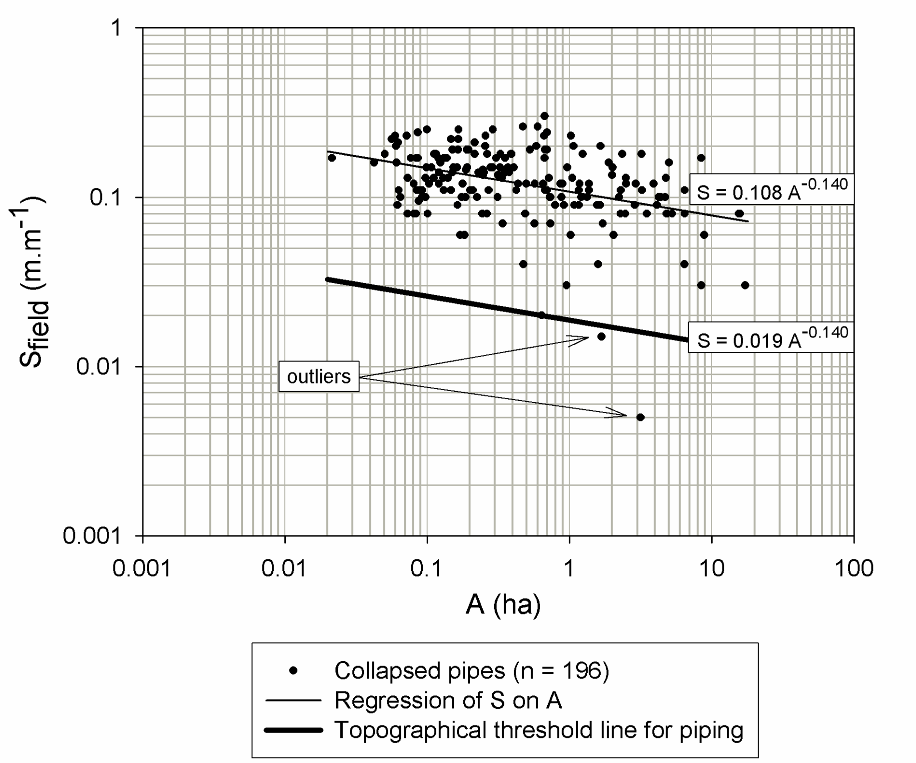


Fig. 4.5. Relation between drainage area (A) versus soil surface slope gradient (S_{field}) of collapsed pipes measured in the field, with indication of the topographical threshold for pipe collapse.

4.4. DISCUSSION

4.4.1. Environmental factors controlling the spatial distribution of collapsed pipes

In clear contrast to surface erosion, most parcels with piping erosion were found under pasture. Piping occurs on a wide range of slopes in the study area, although slopes steeper than 8 % are clearly favoured. In literature as well, the reported slope angles of sites with piping are highly variable. For loess-derived soils, slopes reported range from 10% (New Zealand; Cumberland, 1944) over 11-44% (Germany; Henn and Botschek, 2002) to 30–51% (New Zealand; Gibbs, 1945). An upper-limit value of 12% was reported for the best development of piping in loess covering a clay loam subsoil in New Zealand (Ward, 1966). In this study, 90% of the CP have a slope gradient between 8 and 24%. Some authors suggest that a maximum threshold for the slope gradient is established because on very steep slopes, infiltration generally decreases due to an increase of surface runoff (Jones, 1981) or there is a greater probability that mass movements occur, destroying subsurface pipes (Feininger, 1969; Conacher and Dalrymple, 1977; Farifteh and Soeters, 1999). However, contrasting results were found for this study area concerning landslides. The frequency distribution of landslides with slope gradient was similar to that of piping, and no higher probability of landslides on steeper slopes was observed (Van Den Eeckhaut, 2006). Furthermore, few hillslopes of >24% occur in the study area. We agree with Jones (1981) that the physiographic, hydraulic and pedological context is more important than a specific surface slope.

The requirements for pipe development were summarized by Faulkner (2006) as follows: (a) an infiltrating surface, (b) convergent flow paths and (c) convex profile morphology. The first two are met in our study as the grass cover provides a high infiltration rate and the dominant occurrence of CP in plan concavities suggests convergent flow paths. However, the observations revealed no need of a convex profile curvature. Garland and Humphrey (1992) concluded that the conditions necessary for pipe evolution in the Drakensberg (South-Africa) include concave hillslopes. Jones (1981) as well suggested that most collecting areas from which pipes may run are concave, but that the hydraulic gradient is of greater importance than the surface slope. Later he concluded that many pipes begin on convex hillslopes because desiccation was more important than the concentration of water for pipe initiation (Jones et al., 1997). A higher probability of desiccation is also reported to explain the preference of piping occurrence for a certain slope orientation (Hughes, 1972; Jones et al., 1997; Farifteh and Soeters, 1999). In the studied temperate humid environment, however, desiccation plays a minor role, and instead other mechanisms initiate piping. In addition to water convergence, earthworm activity favours rapid vertical infiltration and mole burrows may favour lateral flow in the soil profile leading to piping. Other authors pointed to the role of animal burrows in the formation of pipes as well (e.g. Carroll, 1949; Czeppe, 1960; Botschek et al., 2002a). It can therefore be hypothesized that piping is triggered by high water tables together with important biological activity (earthworms and moles) in pastures. This leads to other conclusions concerning preferred orientation and plan curvature than those made by studies in environments where desiccation is important.

More hillslopes with CP are facing west compared to the frequency of these slopes in the study area (Fig. 4.3b). This observation is similar to findings about the presence of landslides in the area (Van Den Eeckhaut et al., 2007a). Firstly, the west-facing slopes are steeper, because of the abovementioned valley-asymmetry. Secondly, these slopes are probably also wetter, as rains in Belgium predominantly come from the west (Brisson et al., 2011) and generally more rain falls on the windward side (Blocken et al., 2006). Finally, the loess cover on the west-facing slopes is thinner (Goossens, 1997), which may result in a faster subsurface flow response induced by the clayey lithology. On the other hand, the E–NE-facing slopes have a high probability for piping as well. In our study area, a lower evapotranspiration rate might explain wet conditions on these slopes which could favour piping. Neither the distribution of the clay-rich Aalbeke Member, nor the distribution of the pastures in the study could explain the dominance of certain aspects for sites with piping. In similar conditions, Henn and Botschek (2002) reported the aspect of the slope to be of no importance.

Although piping occurs in a wide range of soils, and soil characteristics other than texture (e.g. structure and infiltration capacity) seem to be of greater importance; soils with a moderate to high silt–clay content are favoured (Jones, 1981). Faulkner (2006) recognized Luvisols, including the loess-derived soils of the study area, as one of the three major soil groups in Europe prone to piping. It is often reported that in-profile variations play an important role in pipe development (e.g. Jones, 1981;

Faulkner, 2006). The so-called ‘duplex’ character has mostly been associated with clay relocation down-profile and subsequent differential swelling and shrinkage and/or permeability differences (e.g. Imeson and Kwaad, 1980; Imeson, 1986; López Bermúdez and Romero Díaz, 1989). This ‘duplex’ condition infiltrating water to horizontal pathways can be interpreted in a wider context, where argillic horizons in loess-derived soil may have a similar effect. In the present study, however, the presence of an argillic horizon (B_t horizon) does not explain the distribution of CP as even more CP are located on soils without profile development. Hence, it can be concluded that loamy colluvium or parent material is suitable material for piping to develop, although it is also logical that the distribution of the soils with colluvium in the landscape (in concavities) is responsible for these results. As sites with piping are favoured by high drainage areas and preferentially are located downslope, these areas are also in a suitable topographical situation to receive sediments from upslope. Consequently, the soil profile development is not likely to create a duplex condition in our study area. Instead, the particular sequence of loess on less permeable clay (Aalbeke Member, KoAa) can act as a duplex condition and give rise to a vertical discontinuity. Strikingly more CP are located in areas with the Aalbeke Member below the loess cover. This lithological layer contains around 50% smectite clay (Van Den Eeckhaut, 2006), impeding drainage. Apart from this, the clay layer at shallow depth plays an important role in the water supply necessary for the enlargement of macropores to pipes. The alternation of permeable clayey sands and less permeable clays gives rise to perched water tables. Due to the dissected topography, these water tables often intersect the surface, and exfiltrating water is discharged as springs (Closson et al., 1999).

4.4.2. Piping initiation slope and contributing drainage area (*SA* relation)

Topographical thresholds are widely used for geomorphological processes, especially for predicting gully initiation (e.g. Desmet et al., 1999; Vandekerckhove et al., 2000; Nachtergaele et al., 2001; Poesen et al., 2003; Vanwalleghem et al., 2005). Some authors pointed to the role that subsurface flow can play in channel initiation and to the influence on the expected *SA* relation (Abrahams, 1980; Moore et al., 1988; Montgomery and Dietrich, 1994). Abrahams (1980) reported that the inverse relation of *S* to *A* no longer applies for channels initiated by subsurface flow. In their theoretical division of the landscape into process regimes in terms of *S* and *A*, Montgomery and Dietrich (1994) expected a positive *SA* threshold line for seepage erosion. This is in contrast to the findings of the present study.

The topographical threshold obtained for piping was compared with those of gullies (Vanwalleghem et al., 2005) and landslides (Van Den Eeckhaut et al., 2007a; Fig. 8). The data from Vanwalleghem et al. (2005) were collected for cropland on loamy soils in central Belgium (loess-derived soils) where both *S* and *A* were based on field measurements. The landslides were surveyed in the Flemish Ardennes in a 710 km² study area including the 153 km² study area of the present study. The average slope gradient for every landslide was calculated by dividing the difference in heights (LiDAR-derived) of the lowest and highest point located within the landslide area by the landslide length (Van Den Eeckhaut, 2006). The drainage areas were calculated with WaTEM/SEDEM similar to those of the CP in this study. To allow comparison with the data of gully initiation, also the threshold based on S_{field} was used for piping. Vanwalleghem et al. (2005) fitted an orthogonal regression (‘reduced major axis solution’; Jackson, 1991) to the data for gullies, but for piping and landslides, ordinary least squares regression was more appropriate because the data were asymmetric (Smith, 2009). The slope of the threshold line for landslides is lower compared to that for the other processes (Fig. 4.6), indicating no important influence of the drainage area. The topographical threshold conditions for piping are similar to the conditions needed for shallow gully initiation. Jones (1981) also reported that piping can occur on gentle slopes when the contributing area is sufficiently large. However, he did not observe a close relation between *A*/*S*-index and the pipe network initiation points nor the pipe discharges (Jones, 1986; Jones, 1997a).

Some critical remarks on the *SA* relation have to be made. The drainage areas used are those derived from the surface topography, assuming that the surface and subsurface drainage areas coincide. It is known, however, that the surface area does not always equal the subsurface area draining to the pipe (Jones, 1986; Jones, 1997a). For our study area, the use of the surface topography is allowed due to the fact that the lithological stratification is subhorizontal. In other studies, the surface drainage area was replaced by other parameters reflecting subsurface catchment size. Jones (1997a) and Holden and Burt (2002) used the maximum dynamic contributing area (DCA) as the best available estimate of the contributing drainage area, with the DCA calculated as the ratio between the total storm discharge in pipe to the total storm rainfall. In this study, however, monitoring pipeflow was nearly impossible in most cases. Most pipes end in feeding the groundwater table which leads to diffuse outlets instead of giving end in a clear bank. Desmet et al. (1999) suggest that unit contributing area, i.e. the upslope contributing area per unit width of contour line ($m^2\ m^{-1}$), should be used instead of *A*. However, this parameter was not applied in the present study, in order to permit the comparison with the *SA* relation from Vanwalleghem et al. (2005).

Pipes are water transmitters rather than collectors, making it possible to cross areas where they receive little or no extra discharge (Weyman, 1974; Gilman and Newson, 1980; Jones et al., 1997). This implies that, when the pipes are essentially carrying water collected from the upper slopes, the calculated *A* of the CP on the mid-slopes can be an overestimate of the real situation. On the other hand, there are factors that are not taken into account in the variable *A* but can increase the water supply to the pipe, such as springs and anthropogenic drainage of roads, buildings and agricultural land. In our database, 30% of the parcels with CP are known to be drained artificially, and 5% of the parcels with CP are affected by concentrated flow generated by road drainage. Because channel initiation associated with road drainage can occur at smaller contributing areas (Montgomery, 1994; Takken et al., 2008), the same can be expected for piping. For channel initiation at road drain outlets, the road contributing area and slope gradient are the most significant explaining parameters, although no clear *SA* threshold could be established (Takken et al., 2008).

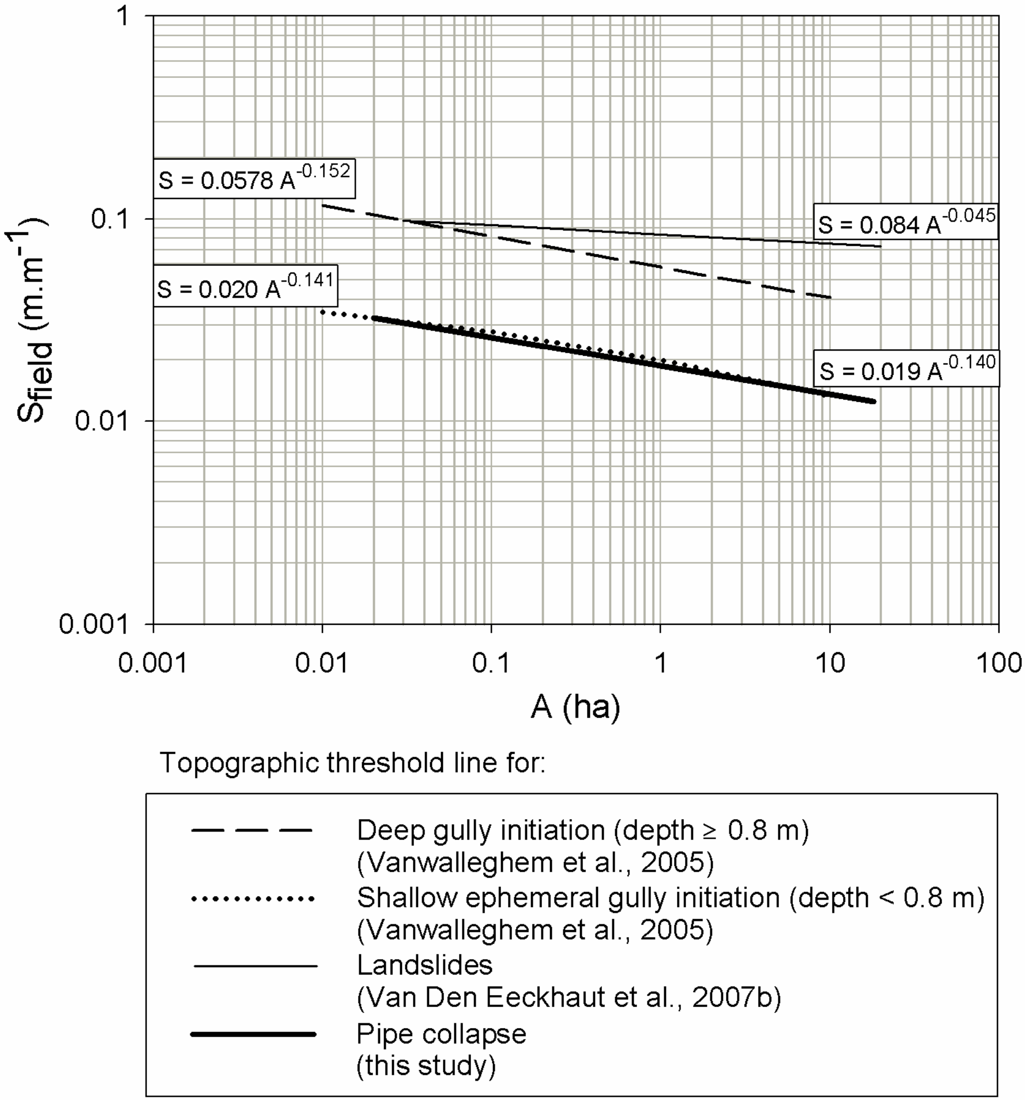


Fig. 4.6. Critical threshold line based on drainage area (*A*) versus slope gradient (S_{field}) for incipient pipe collapse compared to thresholds for landslides in the study area and for shallow and deep gully initiation in loess-derived soils in central Belgium.

4.5. CONCLUSIONS

The loess-derived soils of the Flemish Ardennes in Belgium are susceptible to piping erosion. Different topographical and environmental factors controlling the development of pipe networks and adjacent pipe collapse are reported for regions with other characteristics. This study has confirmed that in loess-derived soils from temperate regions, a wide range of slopes (i.e. 8–24%) can be affected by piping erosion, and that the surface curvature is more important – concentration of water (plan concavities) favours pipe development. The necessary water supply is also enhanced by the characteristic lithology, consisting of an alternation of sands and less permeable smectite-rich clays and giving rise to numerous springs. The presence of a clay-rich lithological layer seems to be an important factor explaining the spatial distribution of the CP in the study area. This may account for the often reported requirement of a vertical discontinuity in infiltration rate in the soil profile. Almost all CP were observed under pasture with 25% of the pastures in the study area located on the clay-rich Aalbeke Member. Furthermore, the presence of high biological activity under this land use may also enhance the vertical (earthworms) and lateral (moles) movement of water although more research is needed to confirm it (Chapter 7). Soil texture, soil drainage class and soil profile development seem to be of less importance for identifying sites with piping within the study area. Nevertheless, the fact that silt material is susceptible for piping erosion is once more confirmed.

Topographical threshold conditions for the collapse of soil pipes have been established. More than the exact slope gradient, the relationship of the slope gradient with the contributing drainage area is important for explaining the occurrence of CP. It can be argued that the surface topography-derived drainage area is not an accurate substitute to the subsurface drainage area of the pipes, due to unknown subsurface topography variations and the influence of anthropogenic drainage changes. Despite this constraint, the *SA* relation is a suitable first attempt, with the parameters that are rather easy to obtain, to identify topographical controls on piping, and to compare them to other erosion processes such as landslides and gully initiation. In this study, a negative power relation was found, similar to the topographical threshold for shallow gully initiation.

Chapter 5

Prediction of spatial patterns of collapsed pipes in loess-derived soils in a temperate humid climate using logistic regression *

5.1. INTRODUCTION

Comparison of an inventory of 560 collapsed pipes observed in the Flemish Ardennes (Belgium; study area of 236 km²) with the soil and lithological map revealed that zones with soil profiles developed on loess covering homogeneous massive clays (Tertiary, Aalbeke Member) were most prone to piping (Chapter 4). Furthermore, 97% of the parcels with collapsed pipes are found under pasture. However, the frequency analysis of Chapter 4 only qualitatively described the factors controlling the spatial occurrence of collapsed pipes in the study area and did not allow to make accurate quantitative predictions for spatial occurrence. There is therefore a need to develop a quantitative approach giving the susceptibility to piping at each location in the study area. This will be a first step towards adjusting local management measures to reduce the potential of soil collapse at a certain site.

Literature about spatial modelling of pipe collapses is very limited and to the best of our knowledge no quantitative predictive model for soil piping has hitherto been proposed. Henn (2002) combined maps of controlling factors (i.e. land use, slope, curvature, soil) to assess piping susceptibility but no quantitative analysis was made. However over the last decade, it has been shown that the location of geomorphic phenomena can indeed be quantitatively analysed so that predictions at a regional scale can be made. Such models have been proposed for karst sinkholes (e.g. Gutiérrez, 1998; Zhu, 2003; Geissen et al., 2007; Galve et al., 2008, 2009), landslides (e.g. Guzzetti et al., 1999; Chung and Fabbri, 1999; Vanacker et al., 2003; Van Den Eeckhaut et al., 2006) and gullies (e.g. Vanwalleghem et al., 2008). These models can take different forms. Guzzetti et al. (1999) describe 5 model types that are used for the assessment of regional landslide hazards: (1) geomorphological models, (2) analysis of inventories, (3) heuristic or index based models, (4)

* based on: Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Govers, G., Deckers, J., 2011. Prediction of spatial patterns of collapsed pipes in loess-derived soils in a temperate humid climate using logistic regression. Geomorphology 130, 185-196.

functional, statistically based models and (5) geotechnical or physically based models.
Contrary to landslides, the mechanics of piping erosion as well as the relative importance of controlling factors are hitherto not fully understood for loess-derived soils in a temperate humid climate. This precludes the use of geotechnical or physically-based models for spatial prediction so that statistical methods have to be used. Nevertheless, the quantitative prediction of the risk for piping is important for at least three reasons: (i) it may help to better understand the factors controlling the occurrence and intensity of piping erosion which may be a first step towards the development of process-based piping models, (ii) it allows better quantification of the contribution of piping to sediment movement at a regional scale and (iii) a regional piping model is a useful tool for land managers that are responsible for zoning decisions.

The objective of this study is therefore to develop a statistical method for the prediction of piping susceptibility in the Flemish Ardennes, a hilly region in Central Belgium. While it is well known that the geotechnical properties of sediments and/or soils control piping, such information is not readily available at the regional scale. Therefore, we also investigated the possibility to create a susceptibility map using topographical information only.

5.2. MATERIAL AND METHODS

5.2.1. Mapping of sites with collapsed pipes and environmental factors

The datasets of parcels with and without collapsed pipes from the survey described in Chapter 4 were used. The term parcel refers to a farmer’s plot mostly limited by fences and ca. 1.5 ha large. Each group of interconnected collapsed pipes within a parcel is named a site. The dataset is based on observed collapsed pipes and the authors are aware that the absence of collapsed pipes does not necessarily mean ‘no piping’ as pipes may be present without reaching the stage of collapse. However, the collapsed pipes are the only data available, given the difficulty to map pipes which did not collapse. Furthermore, the locations with pipe collapse, and thus pipes in a further developed stage, are also more relevant for land management. A description of the methods used to derive topographical variables, lithology and soil information can be found in Chapter 4 (section 4.2.).

5.2.2. Logistic regression

Stepwise logistic regression (Allison, 2001) was adopted to find the best fitting model describing the relationship between the dichotomous response variable (i.e. the presence or absence of a collapsed pipe) and a set of independent explanatory variables. The explanatory variables are continuous or discrete with dummy (or reference) coding, listed in Table 5.1. With dummy coding, each parameter estimates the difference between that level and the reference group. The logistic response function can be written as (Allison, 2001):

$$P(Y=1) = \hat{p} = \frac{1}{1+e^{-(\hat{\alpha}+\hat{\beta}_1 x_1+\hat{\beta}_2 x_2+...+\hat{\beta}_n x_n)}} \tag{5.1}$$

where $\hat{p}$ is the probability of occurrence of pipe collapse, $\hat{\alpha}$ is the intercept and $\hat{\beta}_i$ is the coefficient for the independent variable x_i estimated by maximum likelihood. Eq. 5.1 can be linearized with the following transformation in which the natural logarithm of the odds, $\log(\frac{\hat{p}}{1-\hat{p}})$, called the logit, is linearly related with the independent variables:

$$\log(\frac{\hat{p}}{1-\hat{p}}) = \hat{\alpha}+\hat{\beta}_1 x_1+\hat{\beta}_2 x_2+...+\hat{\beta}_n x_n = \hat{\alpha}+\hat{\beta}X \tag{5.2}$$

Because model fitting by logistic regression is sensitive to collinearities among the independent variables, multicollinearity diagnostic statistics produced by linear regression, i.e. Variance Inflation Factors (VIF) and Tolerance (TOL), were calculated using the SAS© software. Variables with VIF > 2 and TOL < 0.4 were excluded from the logistic regression analysis (Allison, 2001).

Table 5.1. Results of logistic regression modelling for (a) selecting grid cells without collapsed pipes and (b) piping susceptibility assessment.

Variable	*(a) Selecting NCP_{2b} (Step 1, Fig. 5.1)*			*(b) Piping susceptibility, CS model (Step 2, Fig. 5.1)*			
	Input	Coefficients (p < 0.05)	Order of inclusion	Input	Coefficients (p < 0.05)	Order of inclusion	# of models (n = 50) where variable included
Intercept		-2.822			-2.658	0	
Terrain height (m, a.s.l.)	*			*	*		
Slope gradient (%)	X	0.051	1	X	0.157	1	50
Standard deviation of slope gradient	*			*	*		
Upslope contributing area (ha)	X	0.049	2	X	0.190	3	50
Distance-to-thalweg (m)					-0.017	2	50
Plan curvature (m^{-1}) **	X			X		8	
Convergent (concave)		1.709	3		0.666		40
Parallel (straight)		0.821	4				
Divergent (convex)	(r)			(r)			
Profile curvature (m^{-1}) **	X			X		10	
Concave					-0.47		17
Straight							
Convex				(r)			
Aspect				X		6	
North (N)				(r)			
Northeast (NE)							
East (E)					0.778		43
Southeast (SE)					0.670		30
South (S)							5
Southwest (SW)							1
West (W)					0.838		50
Northwest (NW)							
Lithology				X		7	
Clay (KoAa, Ge)					0.515		37
Silty clay (KoMo, KoSm)					0.471		37
Silt-clay-sand (Tt)				(r)			
Sand (Di, Ld)				NP			
Clay sand (Ma)				NP			
Soil texture				X		4	
Silty clay loam				(r)			
Loam, sandy loam					-0.494		50
Sand, loamy sand					NP		
Clay					-2.080		50
Soil drainage				X		9	
Dry				(r)			
Wet					0.481		36
Very wet					0.576		36
Soil profile development				X		5	
Texture/structure B horizon				(r)			
Without profile development					-0.760		50
AUC					0.809		[0.797-0.819]

(r): reference category; NP: not present in the used datasets, but present in the study area; AUC: Area Under the ROC Curve.

* Variables are not included in the logistic regression modelling as they are collinear with other independent variables.

** Surface curvature measurements along the direction of aspect (profile curvature) or the direction orthogonal to aspect (plan curvature).

5.2.3. Database construction

While logistic regression is a suitable technique for the prediction of binary variables, precautions are necessary when there is a significant disequilibrium in the observations. This is the case for our study as the locations where pipe collapse occurs cover only a small fraction of the total surface area. It is therefore necessary to construct a dataset of sites without collapsed pipes that is comparable to the dataset of sites where pipe collapse was observed. The overall methodological strategy we used to do this is illustrated in Fig. 5.1. The collapsed pipes dataset (CP-grid cells) consists of the grid cells where collapsed pipes were mapped (n = 405, Chapter 4). All these cells with a 10 x 10 m resolution enclosed one or more collapsed pipes (n = 560). The construction of a dataset with observations where no collapsed pipes occurred (NCP-grid cells) was less evident. During the field survey and interviews, parcels under pasture where no pipe collapse was observed by the authors nor reported by local residents or owners were mapped as well. A first approach for the construction of a NCP-dataset would therefore be to take a random stratified sample of grid cells out of the NCP-parcels. However, such a dataset can not be directly compared to the CP-dataset because the collapsed pipes in the parcels with collapsed pipes (CP-parcels) are not randomly distributed in the parcel. The collapsed pipes are located mostly on sites with a larger drainage area, a relatively steep slope and a concave plan curvature (Chapter 4). A random selection of grid cells in a CP-parcel may lead to the selection of sites where piping is highly unlikely as well. We therefore considered the known relationships between topographical attributes and the piping risk as observed in the CP-parcels as *a priori* knowledge that was used to construct a NCP-dataset of grid cells that had topographical characteristics similar to those of the CP-dataset.

In order to construct a comparable NCP-dataset, the variables determining the locations with collapsed pipes within a CP-parcel had to be identified (Fig. 5.1 Step 1). Stratified random sampling of grid cells in the CP-parcels, excluding the collapsed pipes as well as a buffer zone in between, was undertaken to create a dataset of NCP-grid cells within the CP-parcels, hereafter indicated as NCP_1. These observations were then combined with the CP-dataset after which stepwise logistic regression was carried out using SAS© software. After exclusion of the highly correlated independent variables, the following logistic model was obtained (Table 5.1):

$$\text{Logit}(\hat{p}) = -2.8220 + (0.0511 * S) + (0.0486 * A) + (1.7088 * \text{concave plan curvature}) + (0.8207 * \text{parallel plan curvature}) \quad (\text{AUC} = 0.717) \qquad (5.3)$$

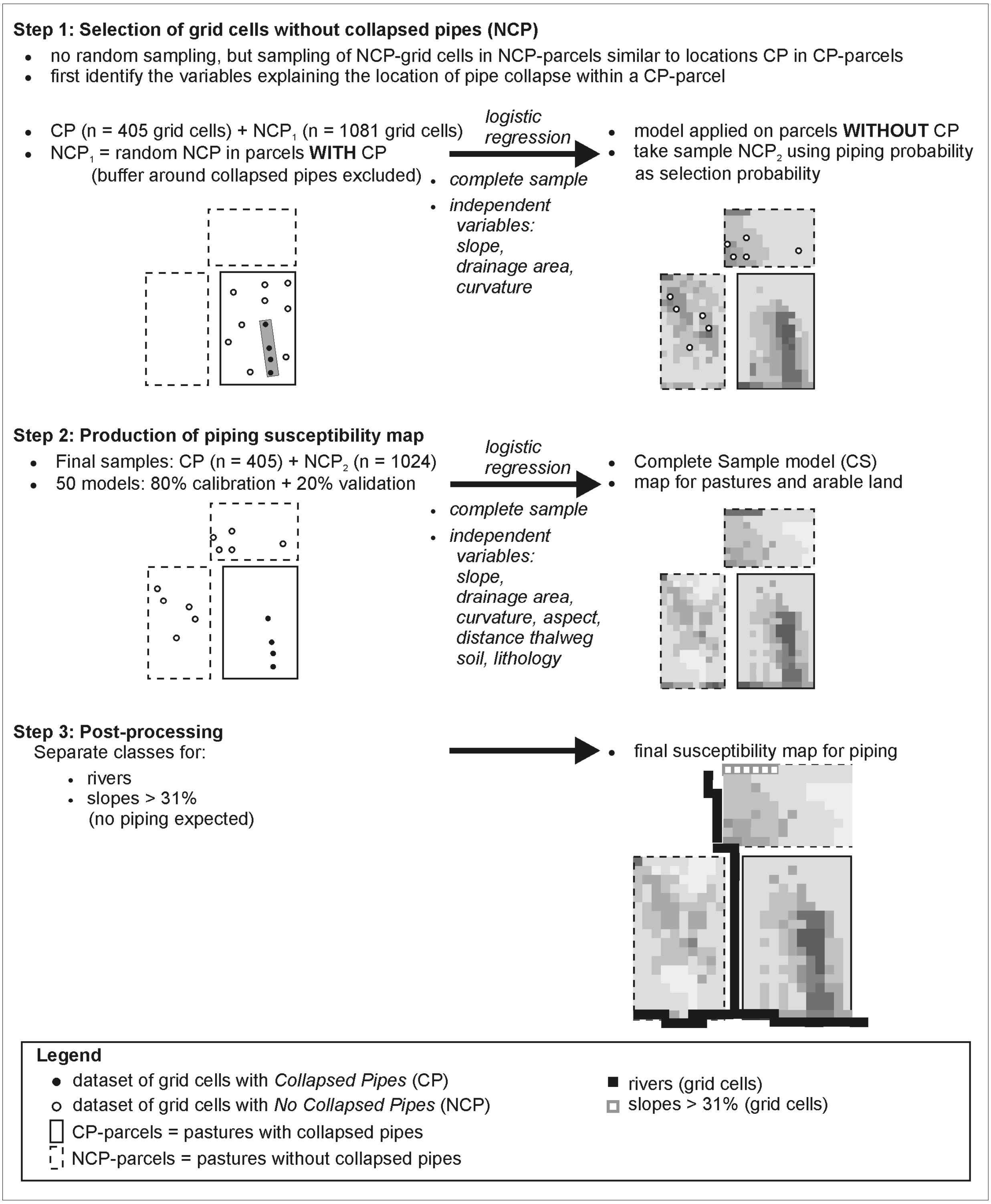


Fig. 5.1. Methodology used for modelling piping susceptibility using logistic regression.

Subsequently, the obtained model was used to produce a probability value for the occurrence of collapsed pipes in each grid cell of the NCP-parcels. Next a subsample (NCP_2) of 1024 observations was taken from the NCP-grid cells using the probability value representing the susceptibility to piping as the probability of selection. Grid cells with a slope gradient >31% (the highest slope gradient that occurred in the CP-dataset) were excluded to prevent exceptional situations which would bias the model (see section 5.3.1.)

Once the final datasets with CP-grid cells and NCP_2-grid cells were defined, the Complete Sample model (CS model) was calibrated using all observations in the CP and NCP_2 datasets (Fig. 5.1 Step 2). After exclusion of the highly correlated independent variables, stepwise logistic regression was carried out. The significance level of the score Chi^2 for entering the model was set at 0.15 and the significance level of the Wald Chi^2 for a variable to stay was set at 0.05. To evaluate the quality of the CS model, stepwise logistic regression was also used to build 50 partial susceptibility models (PS models) using 50 different calibration datasets selected from the final dataset. The 50 calibration sets were produced by taking a random sample of 324 CP-grid cells (i.e. 80%) and 819 NCP_2-grid cells (i.e. 80%). Taking different subsamples for calibration is a method that has been frequently used in statistical classification methods to test the robustness of the model to input changes (i.e. Duarte et al., 2003; Guzzetti et al., 2006; Van Den Eeckhaut et al., 2006; Greco et al., 2007; Van Den Eeckhaut et al., 2010a). The significance levels for model entry or elimination were the same as for the CS model.

Each of the PS models was validated with a validation set that consisted of the remaining 20% of the data not selected in the corresponding calibration set. The appropriateness of the models was further analysed using the ROC (Receiver Operating Characteristic) curve (SAS, 1994). The ROC curve graphically represents the validity of a model by plotting ‘sensitivity’ versus 1-‘specificity’. Sensitivity is the proportion CP-grid cells that are correctly classified as susceptible to pipe collapse (“true positives”) and specificity is the proportion of NCP_2-grid cells that are correctly classified as no collapsed pipes expected (“true negatives”) (Swets, 1988; Lasko et al., 2005). The ROC curve would run vertically from (0, 0) to (0, 1) and then horizontally to (1, 1) for a model with a perfect accuracy. On the other hand, a model performing no better than random guessing would run diagonally from (0, 0) to (1, 1) (Lasko et al., 2005). Consequently, the quality of the models can be validated using the Area Under the ROC curve (AUC) (SAS, 1994). The AUC varies between 0 and 1, with large values corresponding to stronger associations between the predicted and observed values (Allison, 2001). For the 50 models, ROC curves were produced using both the calibration and validation datasets.

Based on the CS model, a piping susceptibility map was created by combining the available topographical, lithological and soil maps corresponding to the output of the logistic regression. Furthermore, 50 PS maps were made for validation purposes only. The created maps show the probability that soil collapse due to piping will occur at that location. As the input dataset consist of sites with collapsed pipes and not piping as such, piping susceptibility in this paper refers to the susceptibility to pipe collapse. In order to facilitate map interpretation, the piping susceptibility map was therefore classified into five classes: very low, low, moderate, high and very high.

5.2.4. Slope-drainage area thresholds for piping initiation (*SA* relation)

In Chapter 4, a topographical threshold for the initiation of piping was identified and can be described by the following equation between the slope gradient (S, m m^{-1}) and the upslope contributing area (A, ha) (Fig. 5.2):

$$S = 0.017A^{-0.123} \tag{5.4}$$

Furthermore, the regression between S (m m^{-1}) and A (ha) for locations where piping occurred could be described as:

$$S = 0.114A^{-0.123} \quad (R^2 = 0.16) \tag{5.5}$$

From this information piping susceptibility maps can be constructed that only account for topographical variations. The regression of S on A (Eq. 5.5) was set as the threshold above which a very high susceptibility to pipe collapse is expected, while Eq. 5.4 was used as the threshold below which no pipe collapse was expected. In addition, two threshold lines were determined in between the previous two allowing 17% and 5.5% of the collapsed pipe data below these thresholds. These four topographical relations allow production of a map indicating susceptibility to pipe collapse in five classes (very low, low, moderate, high and very high).

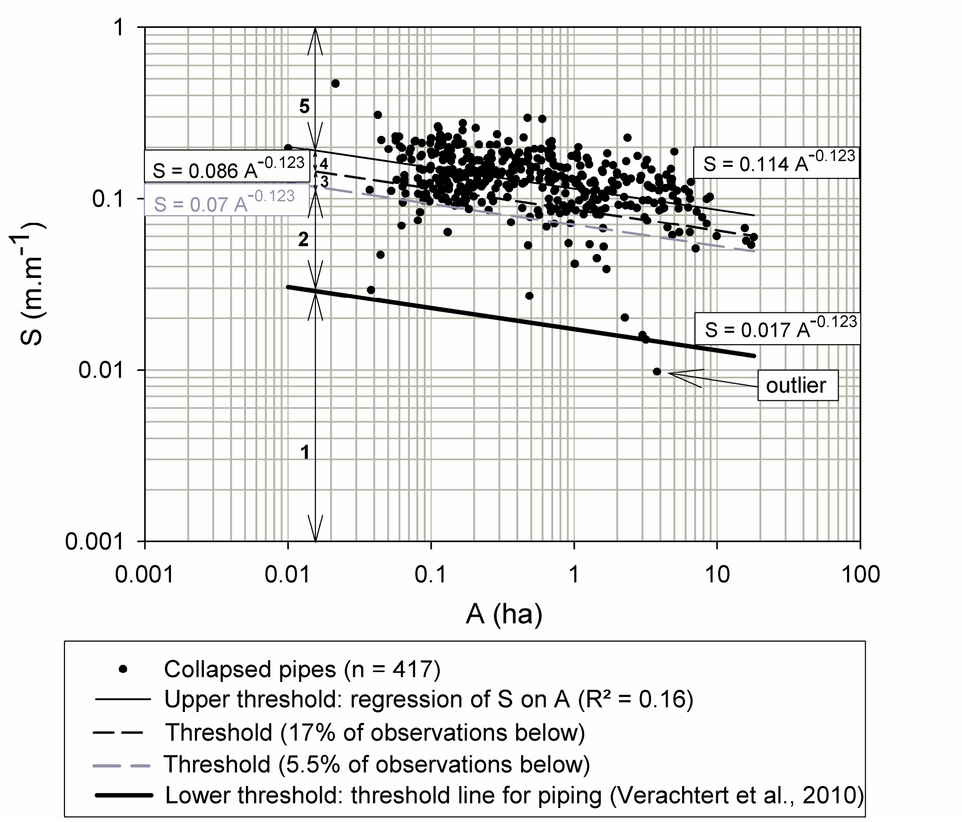


Fig. 5.2. Relation between drainage area (*A*) versus soil surface slope gradient (*S*) with indication of the topographical thresholds for pipe collapse used for classification of the SA derived piping susceptibility map. Piping susceptibility classes: 1 = very low, 2 = low, 3 = moderate, 4 = high, 5 = very high.

5.3. RESULTS

5.3.1. Assessment of susceptibility to pipe collapse using logistic regression

The results of the logistic regression modelling are listed in Table 5.1. Multicollinearity tests (i.e. VIF > 2 and TOL < 0.4) carried out prior to the logistic regression modelling indicated that ‘Terrain height’ and ‘Standard deviation of slope gradient’ were strongly correlated with ‘Lithology’ and ‘Slope gradient’, respectively. Hence, they were not used together in the modelling. For the CS model, Table 5.1 shows coefficients calibrated for the 15 independent variables that significantly (i.e. $p < 0.05$) influence the spatial patterns of CP in the study area. The number of times that a variable was included in 50 models with 50 different calibration sets is given as well. In all the calibrated models the coefficients of the independent variables have the same sign, indicating a consequent positive or negative contribution to pipe collapse. The topographical variables *S*, *A* and distance-to-thalweg are always first included in the model, implying that topography is the most important variable influencing piping susceptibility. To provide more information on the variation of the coefficients within the different models, box plots were produced for each independent variable (Fig. 5.3). As all coefficients of the CS model are located within the 25th and 75th percentile, the CS model can be considered to be reliable. Only the coefficient estimate for concave profile curvature in the CS model is smaller than the 10th percentile from the PS model estimates. The concave profile curvature is only included in 17 of the 50 PS models.

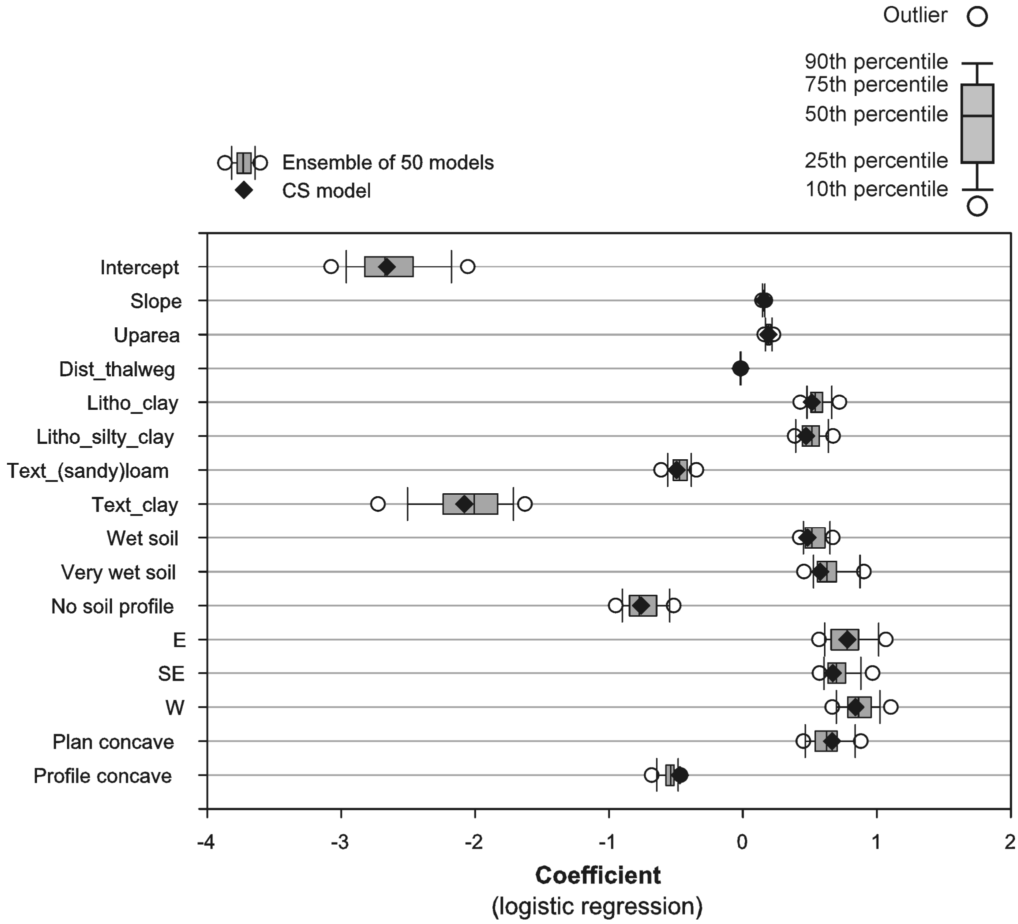


Fig. 5.3. Variation of logistic regression coefficients within the 50 different models, using 50 different combinations of 80% of the data. (Dist_thalweg: distance-to-thalweg; Litho: lithology; Text: texture; Uparea: upslope drainage area.)

Fig. 5.4a shows the ROC curve for the CS model. For the 50 models, ROC curves were calculated using the calibration (80% data) and validation (20% data) datasets (Fig. 5.5a,b). The AUC-values represent a good to very good agreement between the observed and the predicted values. Analysis of the variation of sensitivity and specificity with probability (Fig. 5.4b and Fig. 5.5c,d), allows the assessment of an appropriate classification scheme for the piping susceptibility map. The point where the sensitivity and specificity curves cross is the optimal cut off value between pipe collapse ($p > 0.28$) and no collapse. Given the fact that 2.5 times more NCP-grid cells than CP-grid cells were used, the cut off value can not be 0.5 but will be around 0.28 (i.e. ratio of the number of CP (405) over the total number of grid cells used with and without collapse (405+1024)). Around this cut-off value, there is the most uncertainty. Therefore, a relatively small class with moderate probability is defined around this cut-off value. The other boundaries between the susceptibility classes were set at slope changes of the graphs. Fig. 5.6 shows the susceptibility map after classification. Because slope gradient is included as a positive factor in the model, extreme slope gradients resulted in extremely high probability values. In reality, areas with steep slope gradients are mainly scarps of landslides or areas where exceptional errors in the DEM are present. Therefore, the areas with a slope gradient > 0.31 were put in a separate class. A similar strategy was adopted for the rivers and small streams (Fig. 5.1 Step 3). In this way, the extreme slopes and the rivers could not interfere with the piping susceptibility classes. A detailed example of the classified map is shown in Fig. 5.7 whereby correctly and wrongly classified grid cells are indicated. Table 5.2 gives the corresponding study area and collapsed pipes in each of the piping susceptibility classes.

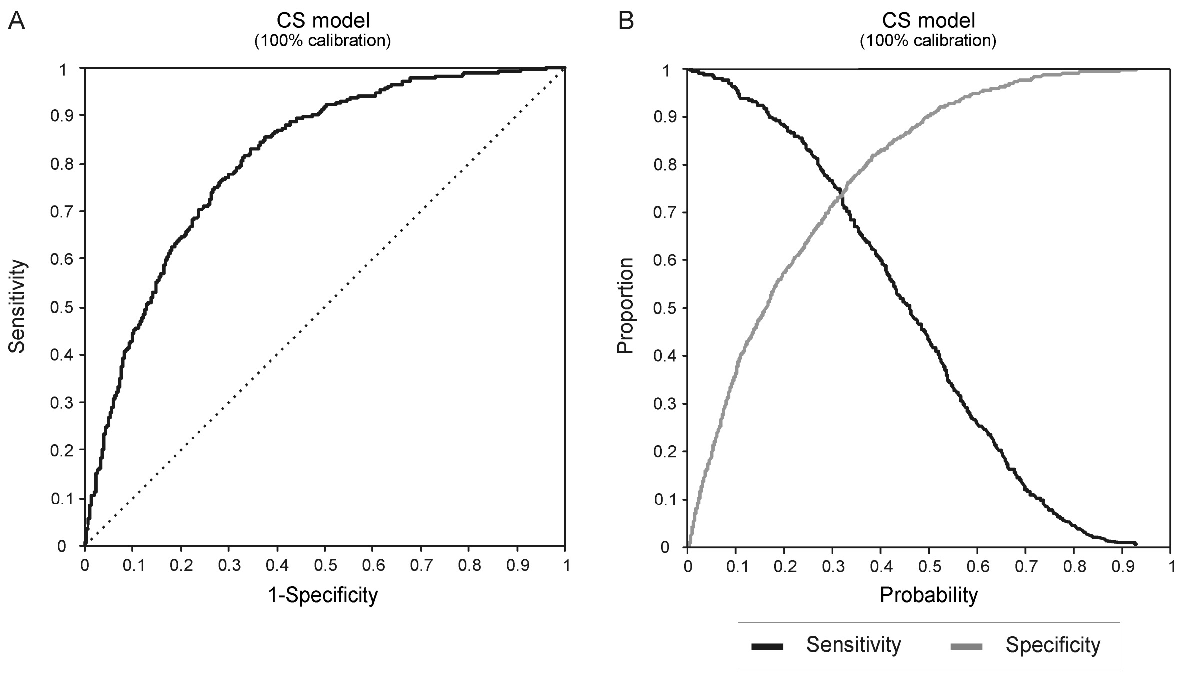


Fig. 5.4. Receiver Operating Characteristic (ROC) curve of the CS model with AUC = 0.809 (A) and evolution of sensitivity and specificity for probability values ranging between 0 and 1 (B)

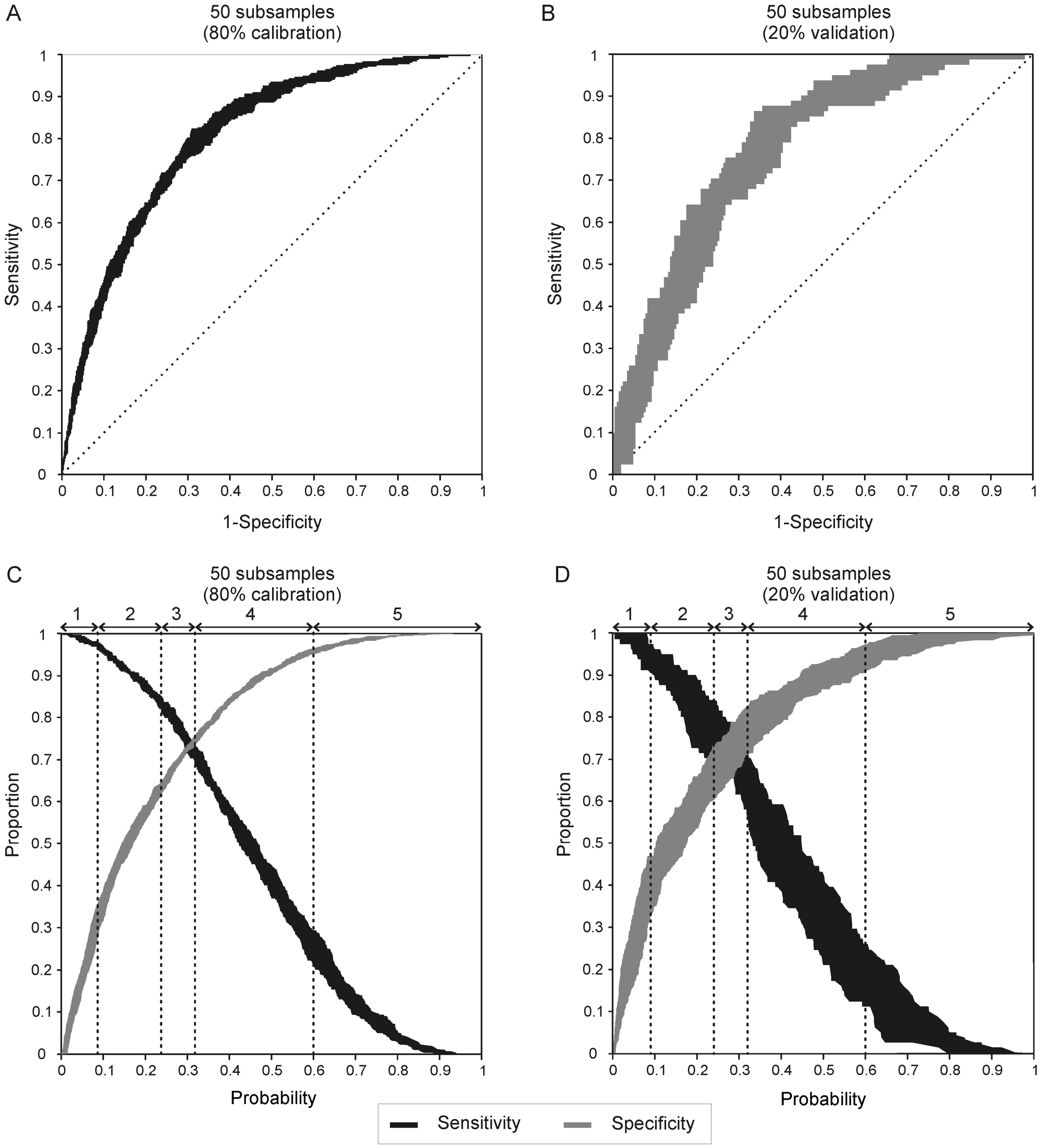


Fig. 5.5. Receiver Operating Characteristic (ROC) curves of 50 calibration (A) and 50 validation sets (B) with AUC values of 0.797-0.819 for calibration and 0.742-0.806 for validation. Evolution of sensitivity and specificity for probability values ranging between 0 and 1, for 50 calibration (C) and 50 validation sets (D). The envelop around all curves is shown. Piping susceptibility classes: 1 = very low, 2 = low, 3 = moderate, 4 = high, 5 = very high.

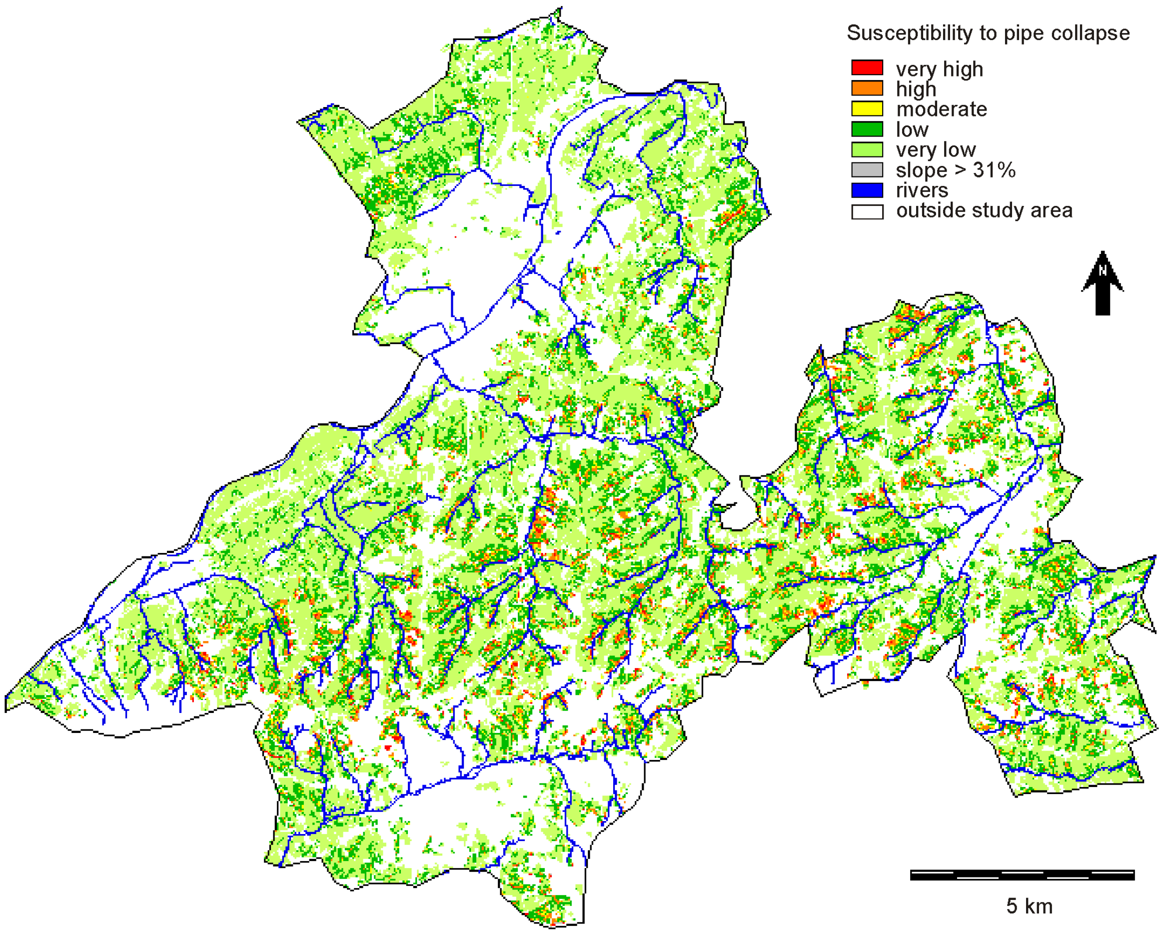


Fig. 5.6. Classified susceptibility to pipe collapse map produced with logistic regression (i.e. CS model).

Table 5.2. Classification in five susceptibility classes to pipe collapse, based on the logistic regression model.

piping susceptibility class		P-value	% study area	cumulative % study area	# collapsed pipes	% collapsed pipes	cumulative % collapsed pipes
0	outside study area[a]				1		
1	very low	0-0.09	60.8	100.0	13	3.3	100.0
2	low	0.09-0.24	26.9	39.2	57	14.4	96.7
3	moderate	0.24-0.32	4.8	12.3	51	12.9	82.3
4	high	0.32-0.6	6.0	7.5	177	44.8	69.4
5	very high	0.6-1	1.5	1.5	97	24.6	24.6
6	slopes >31%				0		
7	river				9[b]		

[a] Study area = pastures and cropland; [b] Collapsed pipes at less than 10 m distance from river (resolution 10x10 m)

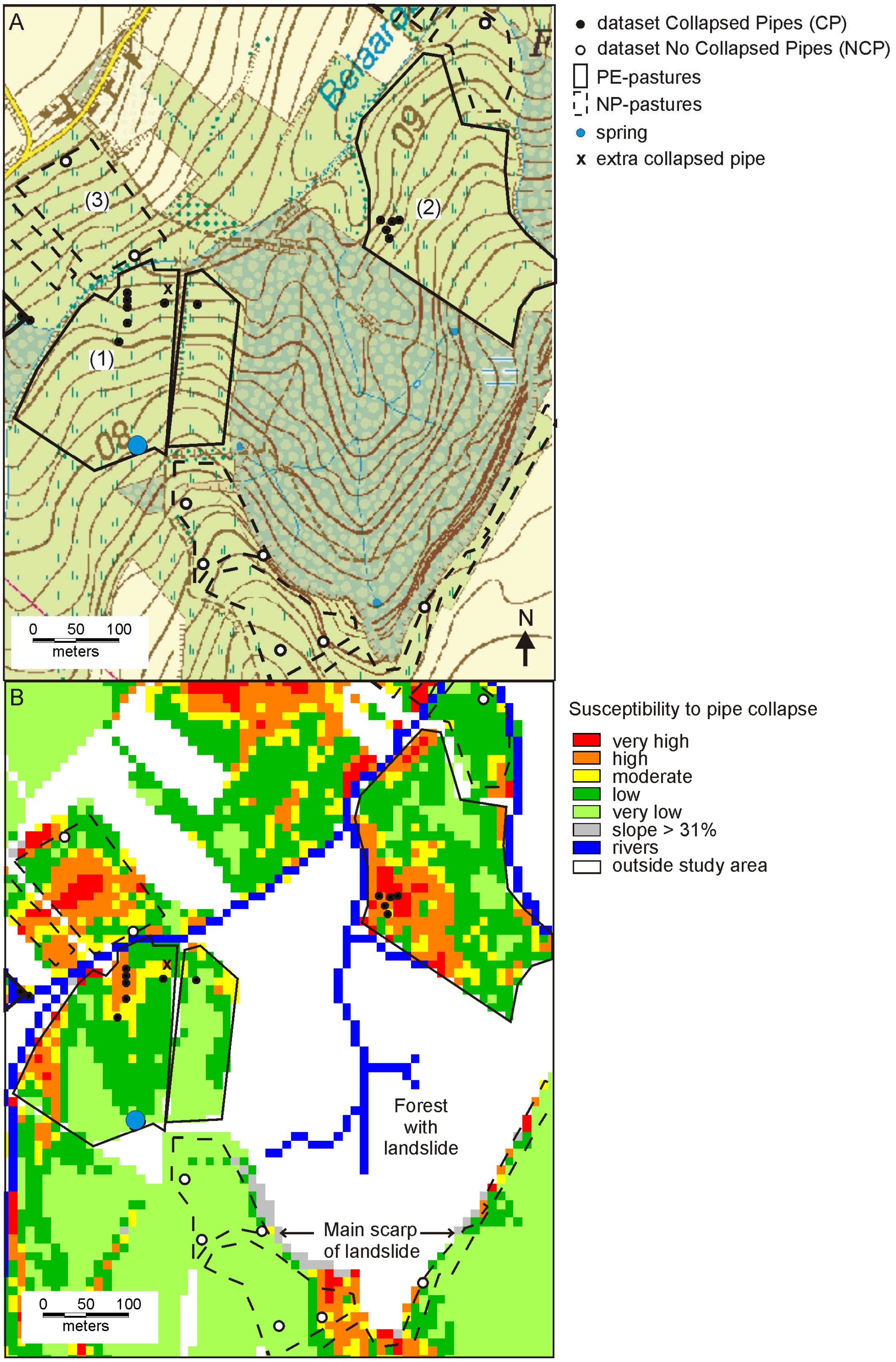


Fig. 5.7. Detail of (A) the topographical map and (B) classified piping susceptibility map produced with logistic regression (CS model), and overlay with the known collapsed pipes. (1) Pasture with most collapsed pipes classified with high susceptibility, also the extra collapsed pipe mapped after modelling (X on map); (2) Pasture with all collapsed pipes classified with high or very high susceptibility; (3) Pasture with a moderate to high susceptibility to piping, but no collapsed pipes were observed.

5.3.2. Piping susceptibility assessment using topographical thresholds

Fig. 5.8 shows the classified piping susceptibility map obtained using the topographical thresholds of Fig. 5.2. The corresponding study area and collapsed pipes in each of the five piping susceptibility classes are given in Table 5.3.

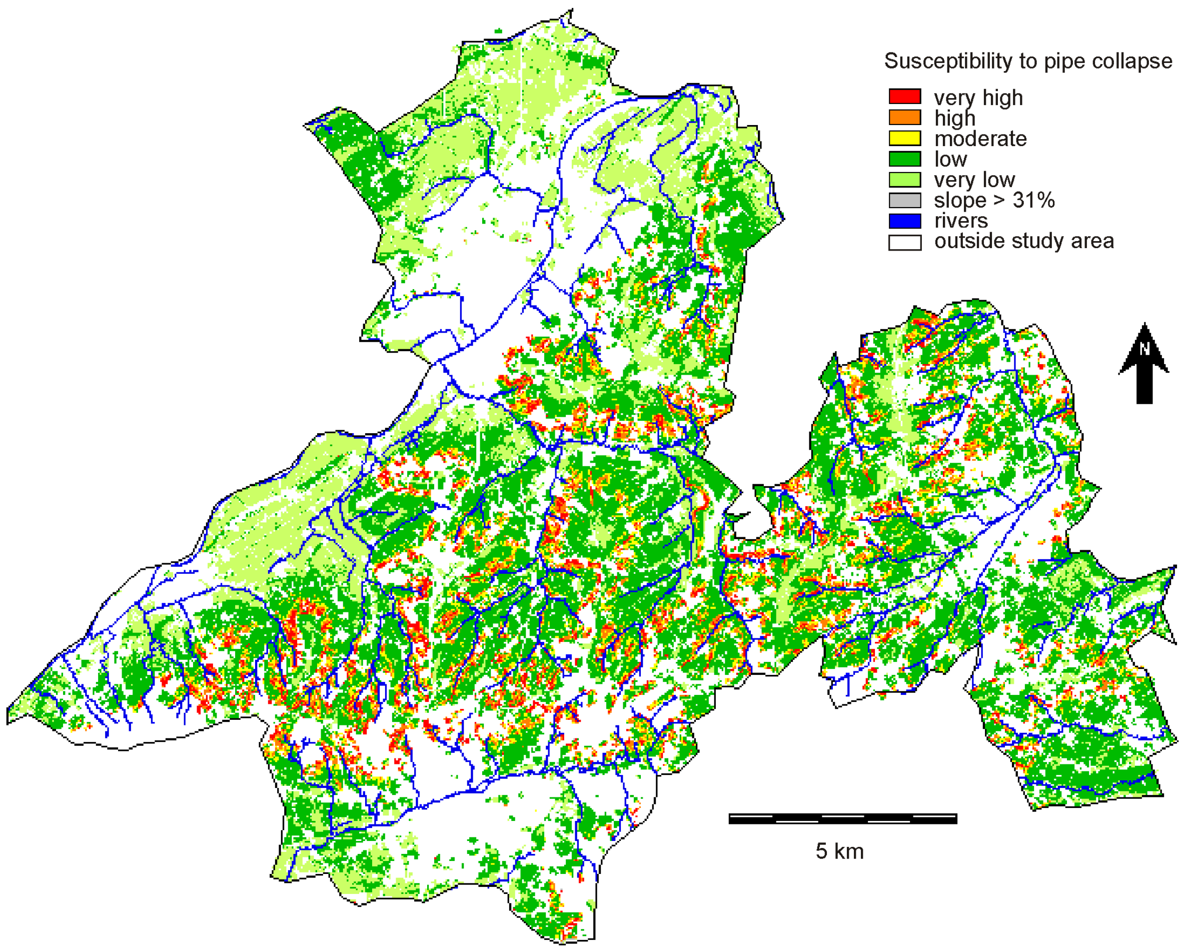


Fig. 5.8. Classified map indicating susceptibility to pipe collapse based on topographical thresholds (SA – relation).

Table 5.3. Classification in five susceptibility classes to pipe collapse, based on topographical thresholds.

	piping susceptibility class	% study area	cumulative % study area	# collapsed pipes	% collapsed pipes	cumulative % collapsed pipes
0	outside study area[a]			1		
1	very low	27.4	100.0	1	0.3	100.0
2	low	54.2	72.6	19	4.8	99.7
3	moderate	7.2	18.4	48	12.2	94.9
4	high	6.7	11.2	112	28.4	82.8
5	very high	4.5	4.5	215	54.4	54.4
6	slopes >31%			0		
7	river			9[b]		

[a] Study area = pastures and cropland; [b] Collapsed pipes at less than 10 m distance from river (resolution 10x10 m)

5.4. DISCUSSION

5.4.1. Interpretation of logistic regression results: factors controlling piping

Besides the susceptibility map, the output of the logistic regression provides information on the factors controlling pipe collapse in the study area. The topography plays an important role, with a positive influence of S and A, and preferentially a small distance to the thalweg. The fact that places where water concentrates and saturation of the (sub-)soil may occur, are susceptible to piping is reflected in the inclusion of the variables concave plan curvature and the soils in a wet or very wet drainage class. Clay-rich lithologies (Tertiary geology below the loess cover) may reflect zones with a shallow water table as well. A more pronounced effect of the lithology was expected. However, only pastures were compared and it is known that more than 75% of the pastures in the study area are located on the silty clay and clay lithological groups (Chapter 4). From the negative effect of the soil texture groups '(sandy) loam' and 'clay', it can be concluded that the collapsed pipes preferentially occur in 'silty clay loam', the reference group. The negative effect of the clay texture is largest, while the effect of (sandy) loam compared to silty clay loam is rather small. This is because subsurface erosion occurs preferentially in loess-derived soils with a sandy loam to silty clay loam texture compared to clayey soils without a significant loess cover. The west aspect was included in all 50 models, while east and southeast were included in most PS models (86% and 60% resp.). As discussed in Chapter 4, the preferential occurrence of pipe collapses on slopes with these orientations cannot be explained by a desiccation probability as reported in other environments (Hughes, 1972; Jones et al., 1997; Farifteh and Soeters, 1999). It is known that the west-facing slopes are the wettest and the steepest in the study area. but it is less clear why pipes occur relatively more frequently on east and southeast facing slopes as compared to other orientations.

Plan curvature, soil drainage and profile curvature were included in 40, 36 and 17 PS models respectively, suggesting that their impact on the occurrence of piping is smaller. The information about the wetness of the soil (soil drainage class) was drawn from the soil map of Belgium which was made way back in 1947 with ca. 2 soil augerings ha^{-1} down to a depth of 120 cm. Drainage classes were based on the depth of the water table below the surface and presence/absence of gley or pseudogley (mottling) colours. It is generally accepted that in Belgium drainage classes are one class drier at present compared to the time of the soil survey, but research for updating the map is currently going on (Van de Wauw and Finke, 2010). The negative effect of concave profile curvature is surprising, but the coefficient is rather small and only represented in 17 out of the 50 models.

One could argue not to use the variables that were already used in the logistic regression model for obtaining a selection of NCP_{2b}. However, the fact that variables such as *S*, *A* and concave plan curvature are still included in the logistic model determining the differences between CP and NCP is an indication of the importance of these variables. Even if we preferentially select the locations in the NCP-parcels with a larger *S* and *A* value, a concave plan curvature and straight profile curvature (thus those grid cells that are in theory most prone to piping), sites with collapsed pipes have a higher drainage area, steeper slope and more frequently a concave plan curvature. Concave plan curvature is not selected in all models (only 40 of the 50), which could be due to the preferential selection of the NCP-sites with a concave profile curvature.

5.5. EVALUATING THE MAPS INDICATING SUSCEPTIBILITY TO PIPE COLLAPSE

5.5.1. Evaluation of the piping susceptibility map based on logistic regression

The logistic regression model resulted in a piping susceptibility map with a good to very good agreement with the observed collapsed pipes. On the CS map, 12.3% of the study area classified as moderately to very highly susceptible to piping contains 82.3% of the observed collapsed pipes. Only 17.7% of the collapsed pipes are located in areas classified with a very low or low susceptibility to piping, whereas these classes comprise 87.7% of the study area. Mostly these false negatives are isolated pipe collapses and/or CP-locations that are less accurate because the pits were already filled up or only small depressions were visible.

Decreasing the number of the false negatives and positives will be very difficult. For example, the hydrological conditions vary over a small distance. The occurrences of landslides in the same area (Van Den Eeckhaut et al., 2006) as well as human activities (e.g. road construction, drainage) influence the situation locally. The drainage area calculated from topography (in a GIS) can be different in the field due to possible differences in subsurface compared to surface area and anthropogenic features influencing the drainage area (e.g. drainage of roads). The landslides in the area may also deviate drainage water through other routes than topographically expected. A critical remark, however, remains that in the inventory only sites where pipe collapse was observed at the moment of survey or where previous pipe collapse was confirmed by local residents, were included. The model indicates all sites that are susceptible to pipe collapse, irrespective of the time frame. Validation of such a map with the piping inventory of a limited time frame has some drawbacks. On the other hand, it is interesting for local management to know which locations are indicative for being susceptible to pipe collapse even if no observations confirm this. This information is important and can be taken into account when considering, for example, a land use change from cropland to pasture or a change in hydrological drainage. Mitigating measures may then be recommended so as to ensure a good drainage of the field by keeping the small ditches operational or by avoiding additional run off from e.g. roads.

5.5.2. Comparison of logistic regression modelling with SA thresholds

Topographical thresholds of *S* and *A* have been used before for predicting gully trajectories (e.g. Desmet et al., 1999; Vanwalleghem et al., 2003) and gully initiation location (e.g. Vandaele et al., 1996; Knapen and Poesen, 2010). Moreover, the topographical threshold conditions for piping are similar to the conditions needed for shallow gully initiation in a comparable region (Chapter 4). Similar to studies for gully initiation, the *SA* thresholds for piping were converted into a susceptibility map. This approach was evaluated as a simple alternative for the more complex logistic regression model where *S* and *A* were one of the most clarifying factors. The resulting susceptibility map (Fig. 5.8) gives a good first indication of the piping susceptibility. On the susceptibility map based on SA thresholds, 11.2% of the study area has a high or very high susceptibility containing 82.8% of the collapsed pipes. These results are comparable to the CS sample map by logistic regression modelling where 12% of the study area also contains 82.3% of the collapsed pipes, although spread over three susceptibility classes (moderate, high and very high). Fewer collapsed pipes are wrongly classified with a (very) low susceptibility than with the CS model (5.1 compared to 17.7%). However, the known places without collapsed pipes are not taken into account. The topographical variables are the most important variables in the logistic regression model as well, but it is not clear at the moment why the simple SA model performs as well as the logistic regression model. This is in strong contrast with findings from the UK where no close relation was observed between the A/S-index and the pipe network initiation points nor the pipe discharges (Jones, 1986; 1997a). Also Holden (2005) found no significant relationships between the topographic index and pipe intensity in blanket peat found in Britain. The soil properties of the studied blanket peat are clearly different (e.g. always wet, very low hydraulic conductivities at depth and hence steep hydraulic gradients even on gentle slopes) from those of the loess-derived soils reported in this study. The location of piping in the peats may be more to do with the history of peat development at a site and the old vegetation that formed the peat over time, or with present land management (Holden, 2005), than with the present topography. In contrast in the Flemish Ardennes, the SA relation seems to represent the spatial distribution of other factors such as lithology as well.

5.5.3. Geomorphological implications

The results of the model suggest that, in this region, piping is driven by subsurface runoff concentration in combination with a sufficient hydraulic gradient. Hence, pipes form mainly in concave thalwegs. One implication is that pipes in this area will generally contribute to thalweg incision: the thalwegs become deeper, which may in turn lead to the intensification of other processes on the slopes. As pipes mainly occur in piping-sensitive (loess-derived) soils, the geomorphological effect of piping will only be present within the loess layer and will not lead to incision into Tertiary substrate.

Some studies report that artificial drainage enhances piping. Artificial surface drainage (moorland gripping) increased pipe density in blanket peats in the UK, potentially due to desiccation in what is otherwise a very wet environment (Holden, 2005; 2006). One could also think that the pipes just form when subsurface drains are broken. However, having loess deposits on a particular site along with a broken anthropogenic drainage tube are not sufficient combined factors to initiate piping and pipe collapse. If we compare the study area with another area around Leuven (Belgium) with loess deposits and sufficient relief, no such collapsed pipes have been observed over the last three decades, only connected mole burrows close to the surface (Govers, 1987; Poesen, 1989). Hence, additional factors are needed for piping and pipe collapse, such as perched water tables which can be induced by the clay-rich lithology in the study area. The other loess area around Leuven lacks this wetness and building up of shallow (perched) water tables.

As almost all collapsed pipes were observed in pastures, only data from pastures were included in the modelling procedure. For all agricultural land, including cropland, the piping susceptibility was calculated as well. The relationship with land use is ambiguous. Land use conversion from cropland to pasture and related macroporosity increase by enhanced biological activity (Chapter 7) may increase piping risk, so it is interesting to know which arable lands are potentially susceptible to piping corresponding to the model. On the other hand, land use is a secondary factor because the pastures are already preferentially located in wet, steep zones with a clay-rich lithology below the loess cover while cropland is mainly found on the plateaus. A similar discussion can be made for forest, added by the fact that conversion from forest to pasture may also lead to a decrease of evapotranspiration rates (van Dijk and Keenan, 2007) hence an increase of subsurface flow. Jones and Cottrell (2007) observed in peat land in the UK a marked reduction in the number and size of pipes after afforestation.

5.6. CONCLUSIONS

Two methods for predicting piping susceptibility were evaluated in this study. A first susceptibility map was created using logistic regression, while a second one was based on topographical thresholds (slope gradient and drainage area). When modelling piping susceptibility to pipe collapse, selecting suitable sites without piping for the model is complex. In the present study, locations of parcels without piping that were similar to location of the collapsed pipes in parcels with piping were selected to allow for correct comparison. The output of the logistic regression model represents the most important factors controlling piping occurrence, i.e. topographical threshold (slope, drainage area) in combination with a sufficient water supply. Topographical water convergence zones (short distance-to-thalweg, concave curvature) and zones with a larger probability of having shallow water tables (clay-rich lithology, wet soil drainage class) are indications for locations susceptible to pipe collapse. The implementation of the model in similar regions is however not evident, because of the complexity of the model. When using only slope gradient and drainage area, the derived topographical thresholds provide a good picture of piping susceptibility in the region. The observation that the *SA* model performs equally well as the logistic regression model only holds for this study area because of the particular relation between topography and lithology. A drawback of this method is that known places without collapsed pipes were not taken into account to create the susceptibility map. Both susceptibility maps can be useful tools for local land management, allowing one to avoid changes in hydrological situation or land use that stimulate piping at locations with a high susceptible to piping even if no observations show this.

Chapter 6
Spatial correspondence between collapsed pipes and landslides

6.1. INTRODUCTION

It has been stated that piping can be both a cause and a result of landsliding (e.g. Pierson, 1983; Jones, 2004a; Hencher, 2010). In some cases, landslides have been reported to enhance piping by the creation of cracks and voids that may be exploited by infiltration and throughflow, leading to pipe development (Jackson et al., 1966; Jenkins et al., 1988; Hencher, 2010). In drylands, Parker (1963) postulated that landslides that blocked the flow of a stream could trigger subsequent pipe development, which could eventually lead to destruction of the landslide-dam by subsurface erosion. Most studies, however, focus on the effects of piping erosion on slope stability and landsliding (e.g. Uchida, 2004). Some reported a positive effect of pipes on slope stability when pipes act as a drain system, evacuating the excess water (e.g. Carling, 1986; Hardenbicker and Crozier, 2002; Hencher, 2010). However, pipe collapse or blockage will lead to a decrease in slope stability (Crozier, 1989; Hencher, 2010). Simulation models (Hardenbicker and Crozier, 2002) as well as flume experiments (Tada et al., 2002; Sharma and Konietzky, 2011) illustrated that blocked pipes reduce the slope stability (factor of safety) and increase the pore water pressure, resulting in an increased probability of slope failure. Others reported that pipes enhance landsliding when they redirect water into susceptible zones of the slope (e.g. Bryan and Price, 1980). Pipes can quickly transmit water from a higher section of the hillslope and cause a larger effective catchment (e.g. McDonnell, 1990; Selby, 1993; Hencher, 2010). Furthermore, pipes near a potential shear plane may reduce underlying support and may increase the probability of failure (Ward, 1966). In forested hills in Japan, 60 out of 64 debris slide scars had at least one pipe and landsliding was linked to pipe blockages (Tsukamoto et al., 1982). Soil pipes have also been reported as a probable contributing factor to landsliding in Tanzania (Temple and Rapp, 1972; Lundgren, 1978), the US (Virginia state; Woodruff, 1971) and Romania (Balteanu, 1986).

This chapter aims at a better understanding of the interaction between collapsed pipeoccurrence and landslide occurrence in the Flemish Ardennes by comparing their respective spatial patterns. The hillslopes of the region are also prone to shallow as well as to deep landsliding. These landslides were mapped by Van Den Eeckhaut et al. (2005; 2007b) who also created a landslide susceptibility map (Van Den Eeckhaut et al., 2006). As we observed that some pipes were located close to mapped landslides and seemed to have similar controlling factors, the objective of this chapter is to analyze the spatial patterns of collapsed pipes and landslides in order to investigate whether or not they occur at the same sites and are therefore linked in one way or another. It is hypothesized that poorly drained landslides change the hillslope hydrology through (i) surface flow obstruction, by changing topography, as well as (ii) subsurface flow obstruction by tilting less-permeable substrates (clay-rich).

6.2. MATERIAL AND METHODS

The location of the 560 collapsed pipes (CP, dataset described in Chapter 3) was compared to the occurrence of 174 landslides (LS) mapped in the same area (236 km²; Fig. 6.1) (Van Den Eeckhaut et al., 2007). Landslides include both recent, shallow as well as old, deep-seated landslides, i.e. landslides having an estimated shear plane depth of less than 3 m and more than 3 m respectively (Van Den Eeckhaut et al., 2005). Old landslides are generally dormant, they are currently inactive but may be reactivated by its original causes or other causes (Cruden and Varnes, 1996). Different positions of CP with regard to LS were distinguished: (i) CP not near a LS (distance > 100 m), (ii) CP next to a LS (distance < 100 m), (iii) CP within the LS affected area and (iv) CP downslope of a LS. As CP upslope of landslides have not been observed in the study area, this class is not present. Similarly, we distinguished LS with and without CP.

The mapped CP and the CP susceptibility map (Chapter 5; five susceptibility classes) were also confronted with the LS susceptibility map of the study area (four susceptibility classes; Van Den Eeckhaut et al., 2006; 2010b). The susceptibility maps were both based on logistic regression using the same spatial input data (topography, soil and lithology; Table 6.1). In the case of the LS map, the individual geological layers (members) were used as input, whereas the corresponding lithologies were grouped together for the CP susceptibility model. The LS susceptibility model incorporated the landslide hillslope gradient, a southeast to northwest slope aspect and the outcrop of a clayey lithology. According to the logistic regression model (Chapter 5), the most important factors causing CP in the study area were the slope gradient in combination with a sufficient water supply, i.e. expressed by a large drainage area, a short distance-to-thalweg, a concave slope curvature, clayey lithology and wet soil drainage class (sites with a large probability of having shallow water tables) in the model. Even though the influence of the topography is decreased in the CP susceptibility model by the method of selecting the pixels without CP (Fig. 5.1), the hillslope gradient is the first variable included in the CP model. A topographical threshold was set for creating the LS susceptibility map as well, i.e. only pixels with a hillslope gradient above 6% were considered. For the modelling of both processes, land cover was not included. Van Den Eeckhaut et al. (2006) did not include land cover as for many of the (currently forested) historical landslides the land cover at the timing of landslide initiation is not known. As mentioned above, we only focussed on pipe collapse modelling under pasture.

As the landslide susceptibility map focuses on the spatial prediction of landlside initiation zones, the (relatively small) classes very high and high susceptibility mainly contain potential landslide initiation areas. However, collapsed pipes are observed to occur rather in the landslide accumulation areas than in the depletion area or initiation zone. On the LS susceptibility map, potential landslide accumulation areas have moderate susceptibility and are located downslope of zones with very high and high susceptibility (Van Den Eeckhaut et al., 2006). The fourth and highest class of the LS susceptibility map (very high susceptibility) mainly contains locations where landslide initiation the very steep slopes, i.e. the LS scarps. Slope gradients exceeding 31% were excluded from the CP susceptibility map (Chapter 5) because no pipes were observed there. Hence, the very high LS susceptibility class is expected to mainly correspond to the class of slopes >31% on the CP susceptibility map in the comparative analysis (Table 6.2). The (very) high susceptibility of CP should be compared to the (very) high –and probably even the moderate- class of the LS map. The comparison of the maps was done using standard routines available in Idrisi Taiga.

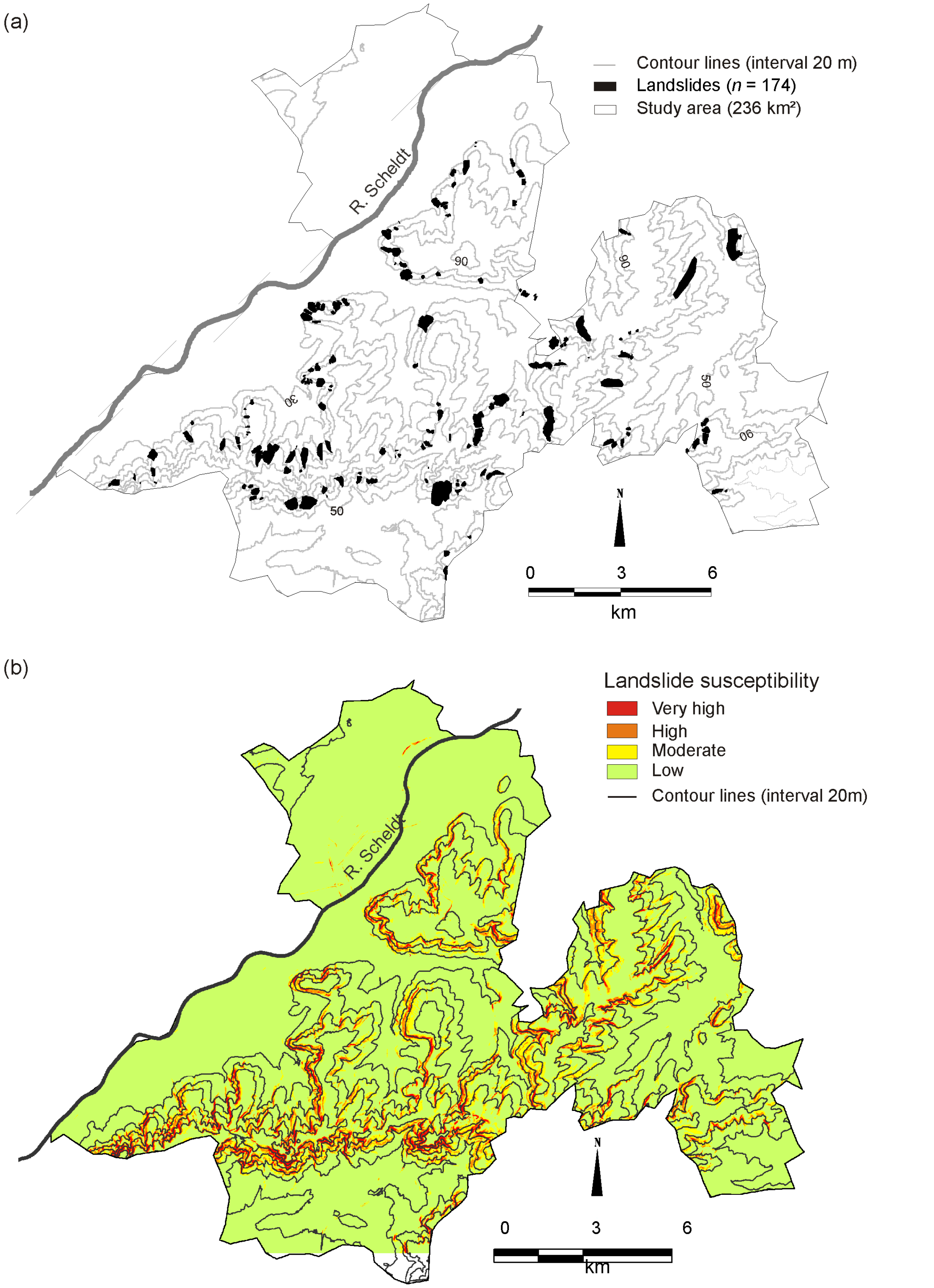


Fig. 6.1. (a) Mapped landslides and (b) landslide susceptibility map of the study area (after Van Den Eeckhaut et al., 2006)

Table 6.1. Comparison of the susceptibility models for landslides (LS) and collapsed pipes (CP) using logistic regression.

	LS susceptibility model			**CP susceptibility, CS model**		
Variable	Input	Coefficients ($p < 0.05$)	Order of inclusion	Input	Coefficients ($p < 0.05$)	Order of inclusion
Intercept		13.418			-2.658	0
Terrain height (m, a.s.l.)				*	*	
Slope gradient (%)		0.386	1		0.157	1
Standard deviation of slope gradient				*	*	
Upslope contributing area (ha)					0.190	3
Distance-to-thalweg (m)					-0.017	2
Plan curvature (m^{-1})						8
Convergent (concave)					0.666	
Parallel (straight)						
Divergent (convex)	(r)			(r)		
Profile curvature (m^{-1})						10
Concave					-0.47	
Straight						
Convex				(r)		
Aspect			2			6
North (N)				(r)		
Northeast (NE)						
East (E)	(r)				0.778	
Southeast (SE)		1.652			0.670	
South (S)		2.399				
Southwest (SW)		2.043				
West (W)		2.948			0.838	
Northwest (NW)		2.520				
Lithology			3			7
Clay (KoAa, Ge)		2.337 GeVl + 2.407 GeMe + 1.381 KoAa			0.515	
Silty clay (KoMo, KoSm)	(r)				0.471	
Silt-clay-sand (Tt)		1.488		(r)		
Sand (Di, Ld)				NP		
Clay sand (Ma)				NP		
Soil texture						4
Silty clay loam				(r)		
Loam, sandy loam					-0.494	
Sand, loamy sand					NP	
Clay					-2.080	
Soil drainage						9
Dry	(r)			(r)		
Wet					0.481	
Very wet					0.576	
Soil profile development		/				5
Texture/structure B horizon				(r)		
Without profile development					-0.760	

(r): reference category; NP: not present in the used datasets, but present in the study area; AUC: Area Under the ROC Curve.

* Individual geological layers (e.g. GeVl, GeMe, KoAa; see Table 1.2) were used in the LS model.

Table 6.2. Classification of landslide and pipe collapse susceptibility classes.

Landslide susceptibility class	Piping susceptibility class	Comparison
1 Low	1 Very low 2 Low	Low
2 Moderate	3 Moderate	Moderate
3 High 4 Very high	4 High 5 Very high Slopes > 31%	High

6.3. RESULTS

Only 24.5% of the sites (i.e. group of connected CP in one parcel) in the study area having CP are located near or on a landslide (grouping of the last three categories), while 75.5% of the sites did not coincide with a mapped LS (Table 6.3a). When looking at the individual CP instead of the sites with one or more CP, a slightly larger percentage (27.5%) was related to a mapped LS. Correspondingly, CP were observed on or near 20% of the landslides in the study area (Table 6.3b). Although most old LS in the study area are now forested, this was different for the LS related to CP. Almost 80% of the LS with CP in their surroundings had pasture or a combination of pastures, forest and arable land as land cover and 17% of these LS were forested but surrounded by pasture. Furthermore, 75% of all parcels with CP contained one or more pixels with high of very high LS susceptibility according to the susceptibility map of Van Den Eeckhaut et al. (2006) (Fig. 6.2). For the parcels without CP (see NCP dataset, Chapter 5), this was only 44%.

Table 6.3. Comparison between the mapped sites with collapsed pipes (CP) and those with observed landslides (LS) expressed as a fraction of the number of sites with CP (a) and expressed as a fraction of the number of LS (b). A site contains one of more connected CP in a parcel.

(a)	**Sites with one or more CP (%)** (n = 139)	**Individual CP (%)** (n = 407)
No LS	75.5	72.5
Next to LS	10.1	14.3
On LS	10.1	9.3
Downslope of LS	4.3	3.9

(b)	**LS (%)** (n = 174)
No CP near LS	80.0
With CP next to LS	8.0
With CP on LS	8.0
With CP downslope of LS	4.0

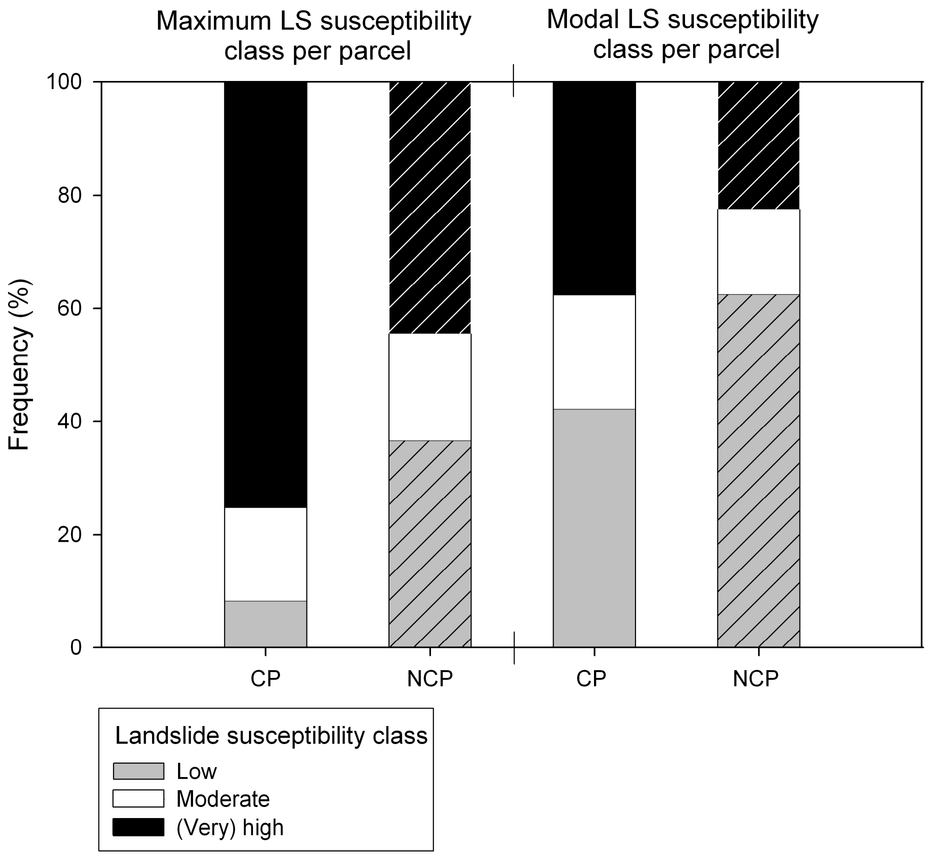


Fig. 6.2. Distribution of landslide (LS) susceptibility class over parcels with collapsed pipes (CP; *n* = 109) and parcels without CP (NCP; *n* = 1013). Maximum per parcel: the maximum LS susceptibility class in a parcel; Mode per parcel: the most frequent LS susceptibility class in a parcel.

When working with mapped CP and mapped LS, the analysis is limited to the sites from both surveys which are deemed to be incomplete. Therefore, the analysis is extended to the whole study area by pixelwise comparison of both susceptibility maps (Table 6.4). The analysis and Kappa Index of agreement indicate a low overall agreement between the both susceptibility maps. However, there is similarity when comparing the variables incorporated in both susceptibility models (Table 6.1). Both models include for example the hillslope gradient and clay-rich substrates. As expected, most slopes >31% (separate class on the CP map) correspond to the very high LS susceptibility class. Half the pixels with a high CP susceptibility were classified with a moderate, high or very high LS susceptibility.

Table 6.4. Pixelwise comparison of the susceptibility map of collapsed pipes (CP) with the susceptibility map of landslides (LS).

Pixelwise comparison		*Susceptibility to LS*			
Susceptibility to CP	low	moderate	high	very high	total
low	1754601	151336	72063	23172	2001172
moderate	82110	18465	13736	6919	121230
high	110111	**38286**	**37922**	**35652**	221971
slope >31%	661	541	961	10519	12682
total	1947483	208628	124682	76262	2357055
Proportional crosstabulation					
low	0.744	0.064	0.031	0.010	0.849
moderate	0.035	0.008	0.006	0.003	0.051
high	0.047	**0.016**	**0.016**	**0.015**	0.094
slope >31%	0.0003	0.0002	0.0004	0.0045	0.005
total	0.826	0.089	0.053	0.032	1

Kappa Index of Agreement (KIA)	*CP as reference map*	*LS as reference map*
low	0.29	0.34
moderate	0.07	0.04
high	0.12	0.23
very high / slope >31%	0.82	0.13
Overall Kappa	0.21	

6.4. DISCUSSION

There is a similarity in the factors controlling the spatial distribution of both piping and landsliding in the study area such as the presence of a moderate slope gradient and less-permeable substrates (clay-rich Formation of Kortrijk). Their occurrence seems not necessarily linked, but in some cases (24.5% of the sites with CP), there spatial association is observed. The association is more pronounced when looking at the predicted susceptibility to LS in the neighbourhood of the CP, i.e. 75% of the sites with CP had a high susceptibility to LS in the same parcel (Fig. 6.2). However, the pixelwise comparison of both susceptibility maps shows that there is a low correspondence in their spatial distribution. It should therefore be mentioned that this comparison only provides a minimum LS susceptibility value of the related sites, because only the exact location (10 x 10 m pixel) is compared and the surrounding pixels are not taken into account. It is possible that a CP or pixel with high susceptibility to CP is located in the accumulation zone of a LS with a lower slope gradient and therefore classified with a low or moderate LS susceptibility, while more upslope or next to the pixel with the CP a high LS susceptibility is predicted. The moderate LS susceptibility class covers the potential landslide accumulation areas, located downslope of zones with very high and high LS susceptibility (see section 6.2). Generally, the land use of pipe collapses and old deep-seated LS differs at present, because most CP occur under pasture while most old LS are under forest now. However, forest was not necessarily the land use at the moment of LS activity. Consequently, for reactivated or new LS in pastures or for LS that are not completely surrounded by forest, there is a higher probability for piping and CP associated with LS.

6.4.1. The effect of landsliding on pipe development

In the study area, 112 CP (27.5 %) were observed within the affected area of 14 LS, next to 14 LS and downslope of 7 LS. There may be an effect of landsliding on the occurrence of pipes in different ways, illustrated in Fig. 6.3. Firstly, LS change the internal drainage of the hillslope by subsurface flow obstruction (type 1). Inclined clay layers block the subsurface drainage (Fig. 6.4). Consequently, subsurface flow searches new preferential flow paths. In this way, LS may create conditions for pipeflow and therefore determine the position of soil piping. Secondly, landsliding causes surface flow obstruction (type 2). The reverse slopes hamper downslope runoff (e.g. from water exfiltrating from springs at the bottom of the main scarp) and increase ponding. From the ponds, the downslope flow is routed around convexities caused by the sliding. It is hard to distinguish both types, but many cases probably are a combination of surface and subsurface flow obstruction. An example from the

Flemish Ardennes is shown in Fig. 6.5. Furthermore, the LS scarp creates a steep hydraulic gradient, which favours pipe development as well (Jones, 1994). In one case, pipes were observed at the main scarp, similar to the pipes observed on earth banks (sunken lanes, lynchets) in our study area and elsewhere in central Belgium (Poesen, 1989; Poesen et al., 1996). This type of piping at earth banks is often initiated due to animal burrows, but was not included in the survey.

At least four reasons can be suggested for the relative small number of sites with CP that coincide with LS. Firstly, the dormant LS are mainly located under forest, a land use where almost no pipe collapse has been observed in the study area (see Chapter 4,.mostly in pastures) over the last decade. Also Jones and Cottrell (2007) reported a reduction in soil pipes after afforestation in peat lands in the UK, who suggest that the reduction is primarily due to a decrease in the amount of throughflow beneath the forest caused by an increase in evapotranspiration. Secondly, for 75.5% of the sites with CP that were not related to a mapped LS, other mechanisms than landsliding may have provided the necessary water supply, such as anthropogenic field or road drainage (i.e. 30% and 6% respectively of the sites with CP, not related to LS). Thirdly, landslides are naturally and artificially drained, especially when under pasture. A well-maintained drainage system (ditch, subsurface drain) will enhance internal drainage and thus, decrease the probability of piping associated to the LS. Finally, both datasets may still be incomplete, which is inherent to historical databases (Malamud et al., 2004). Old landslides that are not visible at present may have been levelled by e.g. tillage operations or land levelling. Old CP may have been filled in by farmers, so that they cannot be observed anymore. We also observed in the study area that small landslides on river banks can push or block rivers, similarly as reported by Parker (1963). In one case, part of the water flow created a subsurface short-cut resulting in piping and pipe collapse, however, these bank slides are not included in the inventory.

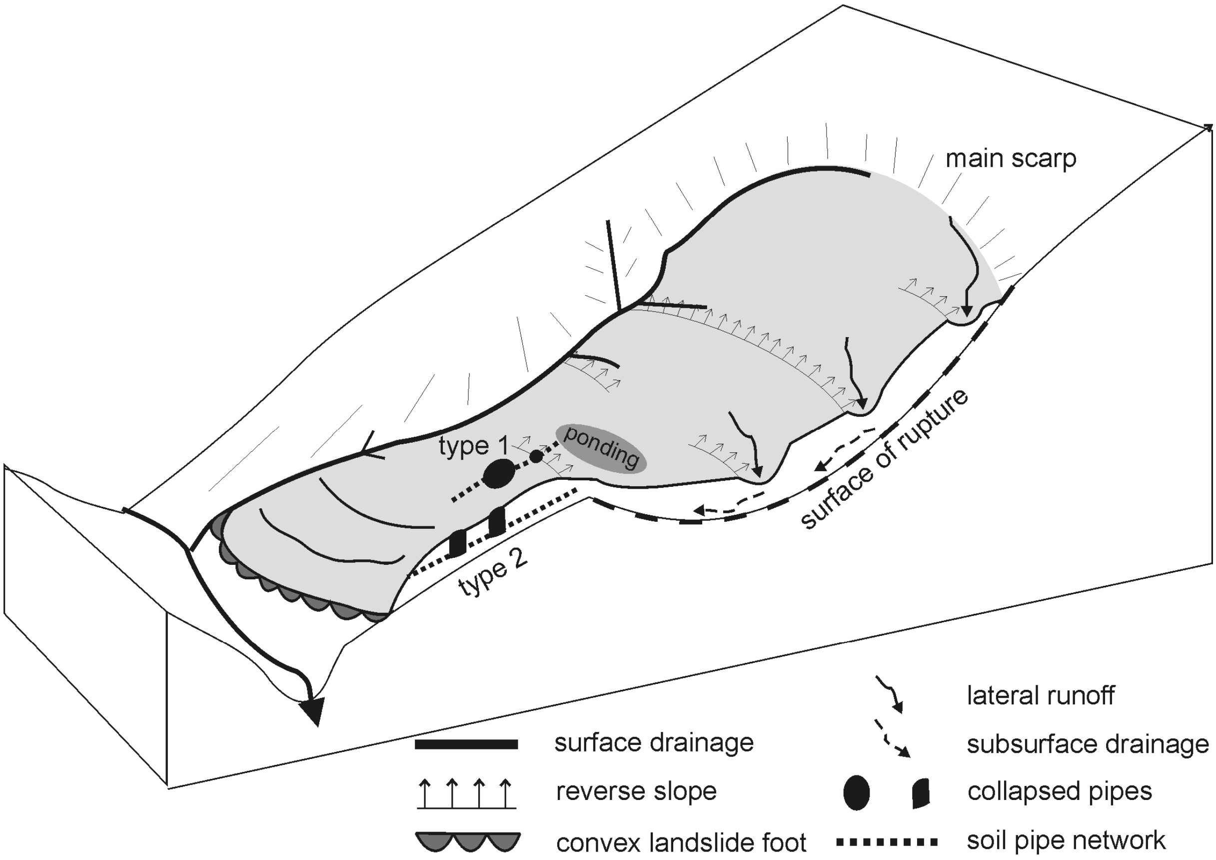


Fig. 6.3. Illustration of the effect of landslides on preferential flow paths. Formation of pipes on the landslide (type 1) and at the border of the landslide (type 2) is indicated. Drainage pattern of the landslide is based on Mather et al. (2003).

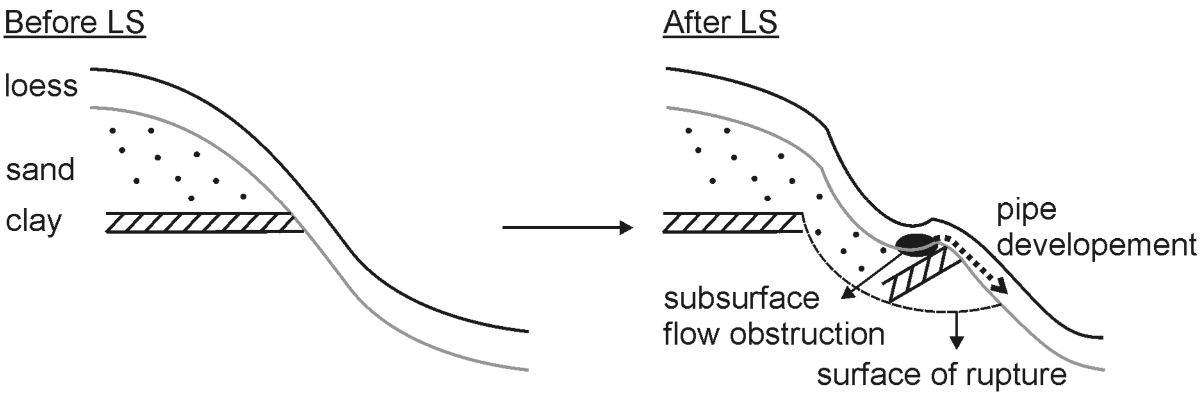


Fig. 6.4. Illustration of the effect of landsliding (LS) on subsurface flow obstruction (type 1) and pipe development (dotted line) at reverse slopes.

Fig. 6.5. Three collapsed pipes (see arrows) in an old landslide under pasture (Koppenberg Oudenaarde, December 2009; J. Poesen). Most probably, they are of type 1, but may also be partly affected by a partial reactivation of the old landslide resulting in a small shallow landslide (dotted line).

6.4.2. The effect of piping erosion on slope stability and landsliding

Most research on the relation between piping and landsliding has focussed on the contribution of pipeflow and piping erosion to slope stability, summarized in a diagram (Fig. 6.6) by Uchida et al. (2001).

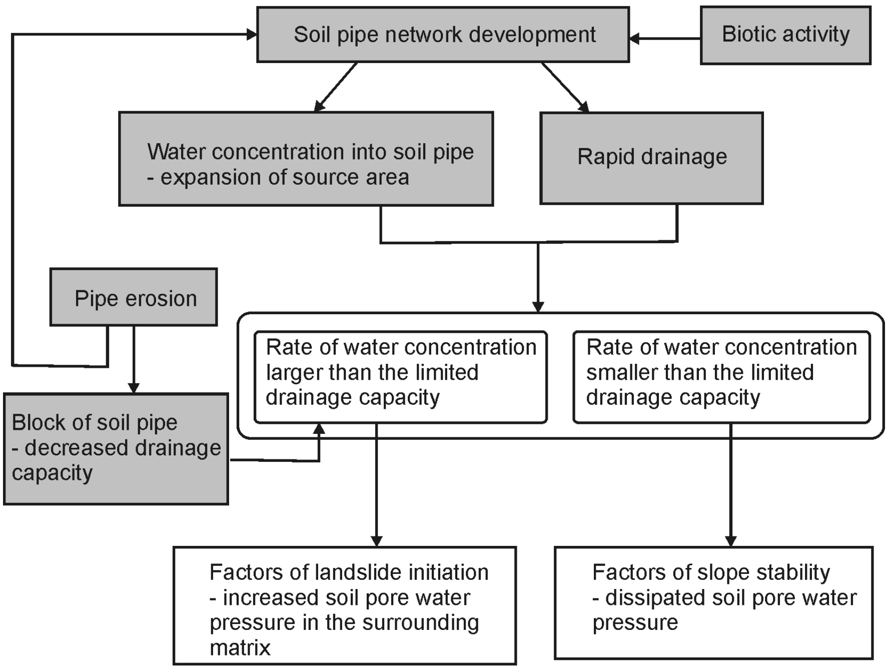


Fig. 6.6. Schematic diagram describing the processes explaining the effects of pipeflow on landslide initiation (after Uchida et al., 2001). The grey boxes indicate similar observations in our study area.

However, the effects on slope stability have not been frequently observed in our study area. It is generally accepted that interconnected networks of soil pipes can rapidly transmit water in hillslopes and may act as a natural drainage system, decreasing the failure probability of the slope. Adversely, if the subsurface runoff concentration is in excess of the pipeflow transmission capacity (e.g. during intense rainfall) or if pipes are blocked (so-called ‘close end pipes’), high water pressures may build up and increase the probability of failure (e.g. Pierson, 1983; Crozier, 1989; Uchida et al., 2001). The fact that almost no subsurface pipes draining water towards the sliding plane of the LS in this study were observed, may have several reasons: (i) there are no pipes upslope of the LS, (ii) the capacity of the pipes is too small to cause an effect or (iii) there were effective pipes, but they are not visible any more as dormant landslides have been initiated a long time ago. The LS scarps are frequently close to the plateaus in the study area, which explains the fact that neither pipe collapses upslope of LS nor pipe outlets in LS scarps were observed. Upslope of the LS, no favourable topographical conditions for piping prevailed as the hydraulic gradient (before landsliding) and the contributing drainage area are too small (Verachtert et al, 2011). The rate of water movement through unstable hillslopes is probably the most important soil hydrological property affecting slope stability (Sidle et al., 1985). Although it has been reported that a connected pipe system may transmit water quickly downslope (McDonnell, 1990), it is still possible that small pipes upslope of the LS were not capable to transmit enough water to trigger landslides in our study area. As pipes are mostly observed within one meter below the soil surface, they probably are too shallow to feed the sliding plane of deep-seated LS. Farmers reported that even if they fill the CP, the next year new pipe collapses occur close to the previous location. This can be an indication that the development of new pipes is favourable above landsliding after pipe blockage. However, as LS reactivations due to blocked artificial drainage pipes were observed in the area, it can not be excluded that blocked pipes contribute to slope instability and LS reactivation.

According to the third reason stated above, the pipes may have been present and may have been effective in decreasing the slope stability, but have not been observed at the time of the CP survey. Most landslides are old landslides, so the situation at the time of slope failure is hard to reconstruct. The survey of the CP was conducted in the period 2007-2009, which are years with a drier winter and spring than those of 1995, 1996 and the early 2000's when new landslides occurred in the study area. Nevertheless, at that time no pipes were observed either in main scarps of those shallow/active LS, often related to existing old LS. Based on his physical model, Pierson (1983) stated that landslide probability is greater downslope of the pipe end, so that pipes may not be observed in the scarps because the landslide reaches not far enough upslope to intersect the pipe. We assume that this does not apply to our study area, where the landslide scarps are often close to the plateaus and where consequently few CP were observed more upslope. In this study, only the CP were mapped, which most probably caused an underestimation of the number of landslides where pipes and piping erosion were involved. Nevertheless, not all blocked or closed pipes will necessarily result in the large build-up of hydraulic head required to change the slope stability: their effectiveness is also affected by the pipe orientation (preferentially (sub)parallel to the slope and to the water table) and the permeability of the soil matrix (Pierson, 1983; McDonnell and Taratoot, 1995). Because of the irregular nature of pipes and their possibility to cause rapid drainage and response to groundwater fluctuations (Premchitt et al., 1986; Chapter 8), it will be even more difficult to predict landslide timing from rainfall when piping is involved.

6.5. CONCLUSIONS

In the Flemish Ardennes, both piping and landsliding occur on hillslopes where similar geomorphological and lithological conditions are present. Therefore, they are observed in the same area, but are not necessary linked. The effects of pipes on slope stability has been well documented in literature, but was not directly observed in this study. This can be attributed to smaller drainage areas on the plateaus upslope of the LS and the lack of a sufficient subsurface discharge through the pipe to create a significant build-up of the water table. Even when pipes get blocked, it is more likely that new pipes develop and new collapses occur than that it triggers LS. This study also investigated the impact of LS on CP, which is less studied. At least 24.5% of the sites with CP were related to the occurrence of mapped LS in the study area. We hypothesize that poorly drained LS change the hillslope hydrology through both surface and subsurface runoff flow obstruction. Hence, LS create new preferential flow paths at reverse slopes (type 1) and at the border of LS (type 2), stimulating piping erosion (Fig. 6.3). Although some of the collapsed pipes could be associated with landslides, landsliding is not a requirement to induce piping as other mechanisms may result in concentrated subsurface flow as well. More attention needs to be paid to signs of piping when LS are reactivated.

Chapter 7

Impact of soil characteristics and land use on piping erosion in a temperate humid climate *

7.1. INTRODUCTION

Piping has been associated primarily with semi-arid environments, yet piping is considered to be a critically important soil erosion process in a wide range of climatic regions (Jones, 1971; Faulkner, 2006). Although topographical variables (sufficient hydraulic gradient, contributing area, curvature) influence pipe development, the subsurface pipe network may owe more to in-profile variations than to surface topography (Jones, 1997a). Preferred locations for piping are just above or within a horizon of low relative permeability (e.g. Fletcher et al., 1954; Jones, 1971) and low aggregate stability (Jones, 1971; Botschek et al., 2002b). For dispersive soils, it has often been reported that pipes typically occur at significant subsurface textural discontinuities in so-called ‘duplex’ soils, which can be explained by differential swelling and shrinking, resulting from differences in clay content and clay minerals with depth (e.g. Imeson and Kwaad, 1980; López Bermúdez and Romero Díaz, 1989). For collapsible loess, an argillic horizon may produce a similar ‘duplex’ character (Faulkner, 2006), but literature about piping in loess-derived soils in a temperate humid climate is rather limited.

Piping may further be enhanced by macropores, which can result from desiccation cracks (e.g. Hughes, 1972; Jones et al., 1997; Farifteh and Soeters, 1999), tectonic joints (e.g. Benito et al., 1993; Farifteh and Soeters, 1999), root channels or animal burrows. Some studies reported that animal burrows were important to piping, as they are effective preferential flow paths providing the necessary pipe flow discharge and subsurface erosion (e.g. Carroll, 1949; Czeppe, 1960; Hosking, 1967 cited in Jones, 1981; Baillie, 1975 cited in Jones, 1981; Farres et al., 1990; Pickard, 1999; Botschek et al., 2002a). Others reported that burrowing animals are only a minor

* based on: Verachtert, E., Van Den Eeckhaut, M., Martínez-Murillo, J.F., Nadal-Romero, E., Poesen, J., Devoldere, S., Wijnants, N., Deckers, J. 2011. Impact of soil characteristics and land use on piping erosion in a temperate humid climate. Catena, submitted.

factor for pipe development (e.g. Fletcher and Carroll, 1948); i.e. they can create inlets for water, but they are not necessary for soil piping. Bond (1941) even studied piping on an island where no burrowing animals are known to exist. In his review, Jones (1981) concluded that “soil biotica may encourage concentration of throughflow in the soil through linear biopores (…), which could develop into pipes, although we have no direct proof of this”.

The results reported in the previous chapters reveal that zones with soil profiles developed on loess covering homogeneous massive clays (Tertiary, Aalbeke Member) are most prone to pipe collapse in the study area of the Flemish Ardennes (Fig. 7.1). Furthermore, land use plays an important role as 97% of the parcels with CP are found under pasture. As there is still uncertainty about the soil properties contributing to pipe development in collapsible soils in temperate climate, this study aims at better understanding the influence of soil properties and land use on pipe development in the loess-derived soils of the Flemish Ardennes (Belgium). Previous studies suggest that soil characteristics play an important role in the development of piping by creating a discontinuity in the soil profile. Therefore, the first objective of this study is to investigate the presence of discontinuities in soil characteristics in 12 soil profiles under different land use (pasture, cropland, forest) with and without CP, more particularly focussing on penetration resistance, bulk density, saturated hydraulic conductivity (K_{sat}) and texture which may explain the development of soil pipes in the loess-derived soils of the study area. As macropores may enhance piping, the biological activity (i.e. by earthworms and mole burrows) will be studied in this research as well as the groundwater levels. Since the detailed soil profile analysis is very labour intensive, only a limited number of soil profiles pits could be studied. Therefore, additional augerings were carried out in order to evaluate the interaction of the groundwater table positions and CP in a larger area. To pursue this objective, the position of the groundwater table in 15 pastures with and 14 pastures without CP was investigated through soil augerings. The aim is to investigate if the groundwater table depth, the soil depth range over which the water fluctuates throughout the year and the Tertiary substrate differ between pastures with and without CP. The positions of the groundwater table will be confronted to the observations on biological activity in the previously mentioned soil profiles. Finally, assuming that biological activity is important for the formation of pipes, it is likely that a transition period is needed before biological activity, induced by a conversion to pasture, has sufficiently developed to induce piping after land use change. Therefore, the third goal of the study is the comparison of the land use history of parcels with CP to that of parcels without CP. Summarizing, the main hypotheses of this chapter are:

(i) discontinuities in aboitic soil characteristics (such as bulk density) or biological activity occur at depths where pipes are present and thus enhance pipe development,

(ii) the groundwater table positions and depth of the Tertiary substrate differ between pastures with and without CP; and

(iii) land use history affects the development of CP because a transition period after conversion to pasture is needed before the biological activity has sufficiently developed to enhance pipe development. .

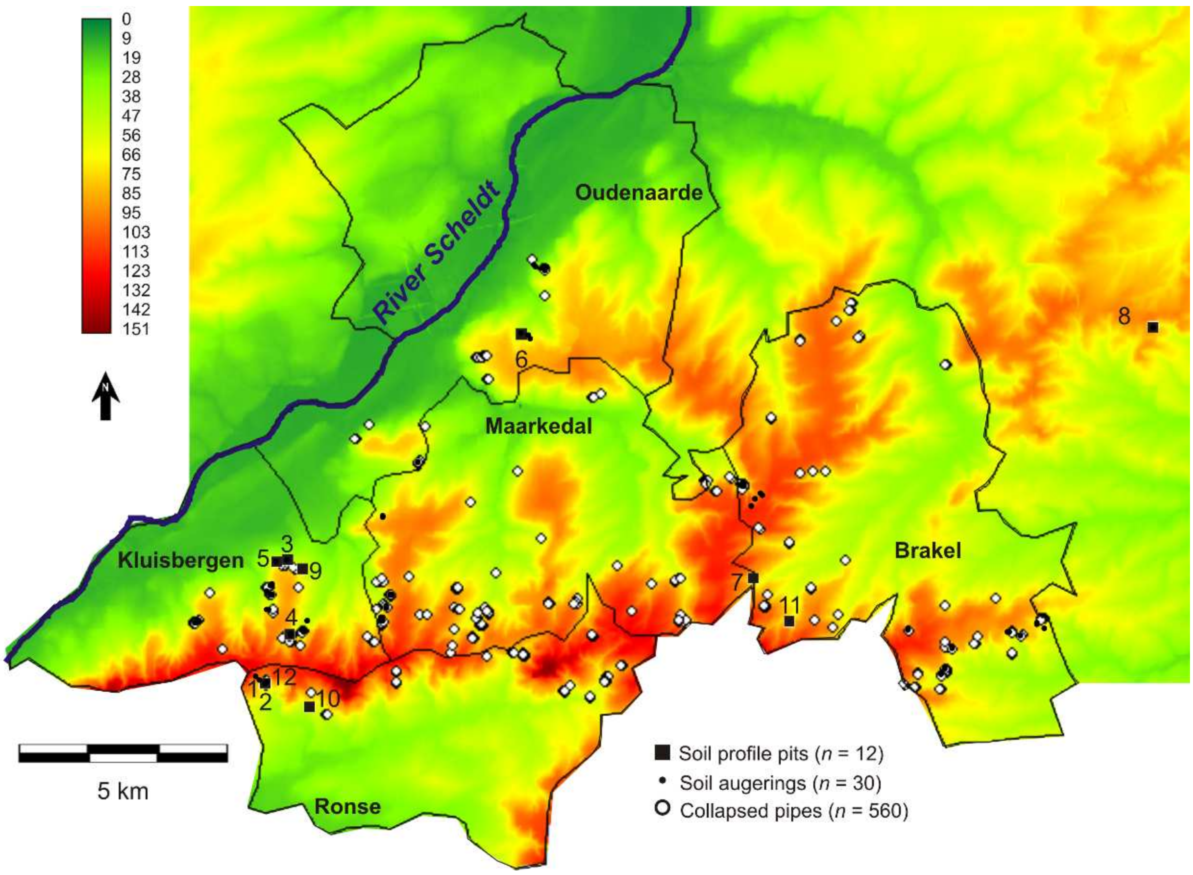


Fig. 7.1. Digital elevation model of the study area in the Flemish Ardennes (Belgium) with the location of the collapsed pipes (CP) and the sites where soil profiles were investigated by means of profile pits: pastures with CP (1=RO5-1, 2=RO5-2, 3=KL9, 4=KL1), pastures without CP (5=Z1, 6=Z2, 7=Z3, 8=Z4), arable land (9=A1, 10=A2) and forest (11=B1, 12=B2); or by means of augerings.

7.2. MATERIALS AND METHODS

7.2.1. Sites and field campaign for determining the soil characteristics via profile pits

Twelve measuring sites with similar geological characteristics (i.e. clay-rich substrate at or upslope of the site), terrain height, slope gradient (S; > 5%) and slope curvature (straight or concave in plan) were selected in the study area: 4 pastures with CP (example given in Fig. 7.2), 4 pastures without CP, 2 sites under arable land without CP and 2 sites under forest without CP. When selecting the sites without CP, it seemed impossible to find sites that matched all the required characteristics, especially when including the upslope contributing area (A; Fig. 7.3). Sites having all the required characteristics had collapsed pipes. Because the presence of a clay-rich lithology was seen as an important factor influencing the occurrence of pipe collapse in the study area (Chapter 4), this criterion in combination with a sufficiently steep slope was used as decisive factor.

Sites selected for soil profile analysis were located near the lowermost collapsed pipe in pastures having CP. At the other measuring sites, profile pits were dug at more or less similar topographical locations. Soil profile pits were dug at the selected sites down to at least 40 cm below the pipe at sites with CP and down to a similar depth (1.40-1.80 cm) on sites without CP. For each profile pit, a complete soil profile description was made. This also included mottling features (oxidation colours) indicating the depth of the winter water table (WWT, mottling; Fig. 7.4a) and reduced soil colours (white/grey matrix) and/or water observation indicating the summer water table (SWT, groundwatergley; Fig. 7.4b). The upper boundary of the WWT (mottling) is taken as the soil depth where 20% mottling was observed. At the same location, horizontal cross sections (1 m²) at different soil depths were made, with depth intervals (20 - 60 cm) varying according to soil horizons of the site. The following characteristics were studied for the different horizontal cross sections: (1) K_{sat} (measured with a double ringinfiltrometer), (2) biological activity (density of open and closed channels from earthworms (*Lumbricus terrestris* L.) and burrows from moles (*Talpa europaea* L.) evaluated on horizontal sections of 1 m²), (3) soil penetration resistance (horizontal resistance with manual penetrometer, Eijkelkamp© type IB; vertical resistance with a digital penetrologger, Eijkelkamp© type 06.15.SA after saturating the soil layer and allowing it to drain for minimum 24 h), (4) texture (LS 13

320 Laser Diffraction Particle Size Analyser of Beckman Coulter©) and (5) soil moisture content. Only K_{sat} measurements were made at a second profile pit, next to the first one, in order not to disturb the other measurements (e.g. biological channels) while saturating the soil. At each depth, 3 ring infiltrometers with diameters of 10 cm and 20 cm for the inner and outer ring respectively and a height of 20 cm were installed. While counting the number of earthworm channel cross sections, open and closed (filled up with excretion or soil material) channels were counted separately, using toothpicks (Fig. 7.2b).

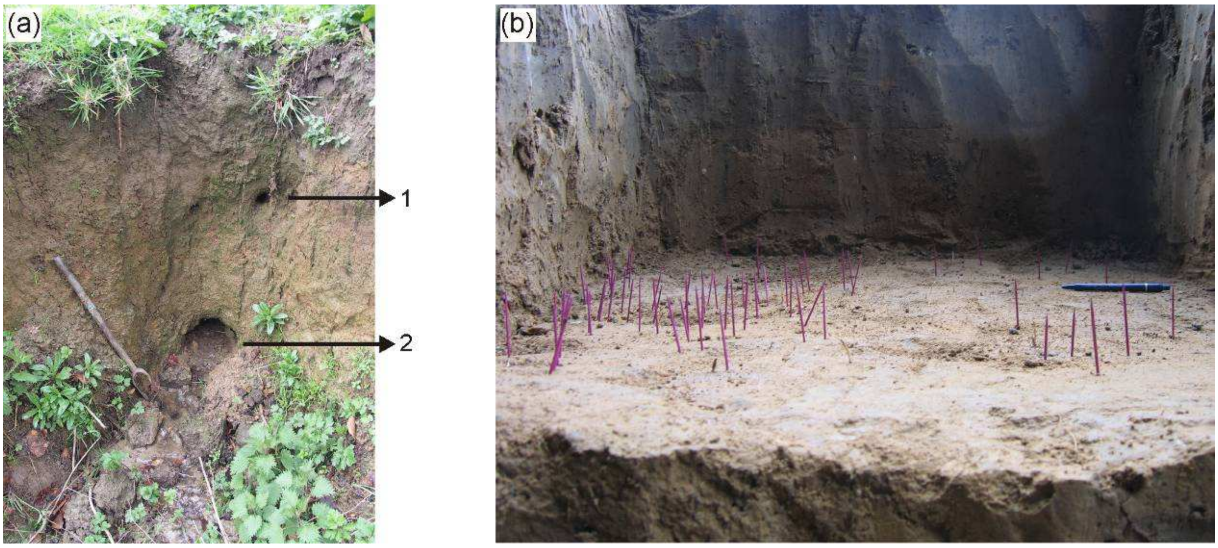


Fig. 7.2. (a) Soil profile RO5-1 under pasture with indication of a mole burrow at a depth of 60 cm below the soil surface (1; cross section is ca. 6 cm;) and soil pipe at a depth of 140 cm (pipe bottom) below the soil surface (2; cross section is ca. 20 cm;). The length of the soil auger segment on the left equals 50 cm; (b) Horizontal soil cross section of ca. 1 m² at a depth of 60 cm with toothpicks installed for counting earthworm burrows (Ronse, March 2008).

7.2.2. Sites and field campaign for determining the depth of the groundwater table via augerings.

Since piping erosion occurs mainly in pasture in the study area, the analysis of the depth to the phreatic water table by augerings focussed on pastures. 15 pastures with and 14 without CP were selected from the dataset described in Chapter 4. Local geology was not used as a selection criterion for the sites without CP. Instead, the sites without CP were selected to cover the same range of S and A values as the sites with CP. For both pastures with and without CP, the relationship between S (m m^{-1}) and A (ha) was determined. A regression line was fitted through the scatter plot for both the sites with and without CP to evaluate differences in topographical positions (Fig. 7.3). All studied sites are characterized by values of S and A larger than the topographical threshold line for pipe collapse determined in Chapter 4. The two regression lines are not significantly different (p > 0.05). According to the logistic regression susceptibility map (Fig. 5.6), 86% of the selected sites with CP had a (very) high susceptibility to pipe collapse compared to 24% of the selected sites without CP.

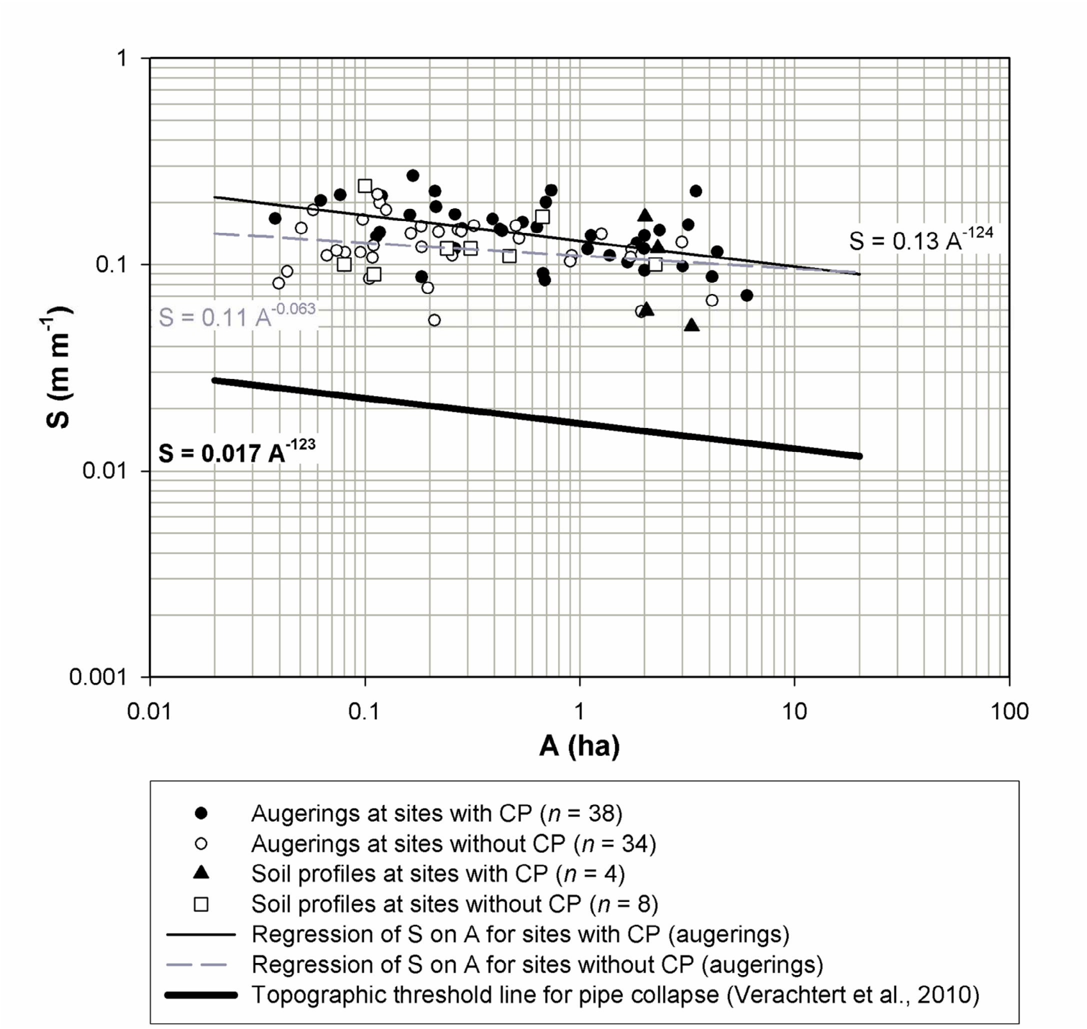


Fig. 7.3. Slope-drainage area relation for the selected sites with and without collapsed pipes (CP).

At each pasture with CP, soil augering was done at the most upslope and most downslope collapsed pipe. Similar topographical positions were selected for pastures without CP. For each augering, the soil texture changes, the SWT (groundwatergley; Fig. 7.4b), WWT (mottling; Fig. 7.4a) and depth to the Tertiary substrate below the loess cover were described at the end of the summer (September 2009). Because mottling only indicates the highest position the groundwater table has been once for several consecutive days, augering is done again at the end of the winter (March 2010) at the same sites to determine the WWT position at that moment (WWT, groundwatergley). The maximum depth of the augerings was generally 3 m, because the research focuses on depths that are of influence to pipe development in the area. Augering is stopped at less than 3 m when WWT, SWT and Tertiary substrate are observed at more shallow depths. The groundwater fluctuation zone (FZ) is the depth over which the groundwater table fluctuates and is calculated as the difference between the SWT (groundwatergley) and the WWT (groundwatergley). A change in soil texture and/or colour indicates the limit between loess and the underlying Tertiary substrate.

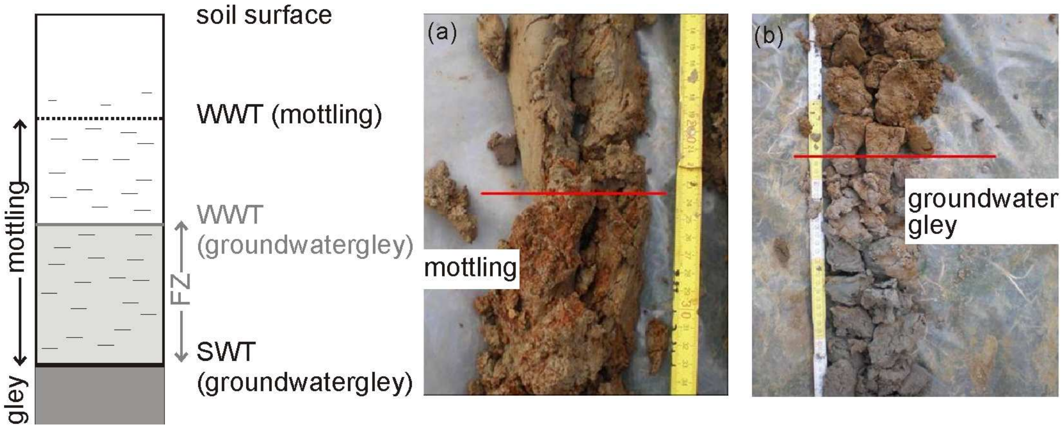


Fig. 7.4. Colour changes in augured material of a soil profile at the end of summer, indicating (a) the upper boundary of > 20% mottling starting and defining the highest position that the winter water table, WWT (mottling), has ever been for several days, and (b) reduction colours (groundwatergley), defined as the summer water table, SWT (groundwatergley).
The level to which the reduction features rised at the end of winter is further referred to as WWT (groundwatergley), indicated in grey. The groundwater fluctuation zone (FZ) is the soil depth range over which the groundwater table fluctuated.

Detailed statistical analysis of the soil profile characteristics is not possible because of the limited number of profile pits. Statistical tests on the dataset from the augerings were not straightforward either, as augerings were stopped at 3 m depth and the soil data for sites where the groundwater table was deeper were included in the tests attributing them the value of 305 cm. Nevertheless, differences in mean (t-test) and median (non-parametric Wilcoxon test) groundwater table positions between sites with and without CP could be statistically evaluated, separately for upslope and downslope sites as well.

7.2.3. Sites and maps used for land use analysis

For investigating the influence of the land use history on piping erosion, the past land use is determined by analysis of a time-series of 10 maps from 1777 until present (Table 7.1). The land use history was investigated for 76 known pastures currently affected with CP in the municipalities Maarkedal and Brakel, 8 pastures currently affected with CP in the surrounding municipalities and 84 pastures without CP (at the moment of survey) having similar topographical characteristics.

Table 7.1. Historical maps used for the analysis of land use history of pastures with and without collapsed pipes (CP) in the municipalities of Maarkedal and Brakel.

Map	Year field recording	Year published	Number of parcels*	
			With CP	No CP
Ferraris	1770-1776	1777	84	84
Military maps	NK	1824	69	68
Vandermaelen	1831-…	1850	84	84
Military geographical institute	1884	1895	84	84
Topographical map	1950-1953	1957	84	84
Topographical map	1950-1953, 1959-1960	1963-1964	84	84
Topographical map	1974	1977	84	84
Orthophotos	1990	1992	63	63
Topographical map	1995	2000	84	84
Orthophotos	2006	2006	84	84

*As some map sheets are missing, not every parcel could be analysed on every map.
NK = not known.

7.3. RESULTS

7.3.1. Detailed soil profiles

Table 7.2 shows the characteristics of the selected sites where soil profile pits were opened. Soil pipes of the four studied profiles with pipes were observed, on average, at 114 cm depth (i.e. centre of the soil pipe at 70, 124, 130, 132 cm respectively). The contributing area for the pastures with CP (mean 2.43 ha) was larger than for the other sites (mean 0.53 ha; Fig. 7.3). The position of the groundwater table at the end of the summer for the pastures with CP (at less than 2 m from the surface for 3 out of the 4 sites) was higher as well compared to the other sites (all having a water table at > 2 m from the surface).

Table 7.2. Characteristics of the selected sites with and without collapsed pipes (CP).

Land use	Site name	Depth to pipe[a] (cm)	Lithology[c]	Slope (%)	Contributing area (ha)	Spring upslope[d]	Waterflow in pipe (summer)
Pasture with CP	RO5-1	130	KoAa	12	2.31	yes[e]	yes
	RO5-2	132	KoAa	5	3.31	yes	no
	KL9	124	KoMo with KoAa upslope	6	2.04	yes	no
	KL1	70	KoAa	17	2.01	yes	yes
Pasture without CP	Z1	NP[b]	KoMo with KoAa upslope	17	0.67	no	NP
	Z2	NP	Tt and KoAa	10	0.08	no	NP
	Z3	NP	KoAa	11	0.47	no	NP
	Z4	NP	Ge	24	0.10	no	NP
Arable land	A1	NP	KoMo with KoAa upslope	9	0.11	no	NP
	A2	NP	KoMo with KoAa upslope	10	2.25	yes[e]	NP
Forest	B1	NP	KoAa	12	0.31	no	NP
	B2	NP	KoAa	12	0.24	yes	NP

[a] Depth to pipe indicates distance between soil surface and centre of pipe channel; [b] NP: No pipe; [c] Lithology derived from Tertiary geological map (1:50,000; AGIV, 2001a) with Ge (Gent): glauconitic sand and clay with sand lenses, Tt (Tielt): glauconitic clayey sand, with clay and lithified sand layers; KoAa (Aalbeke): homogeneous blue massive clay; KoMo (Moen): clayey silt to sand with clay layers; [d] Field observations; [e] Drainage water from road.

Soil profiles with pipes did not have clear profile discontinuities for the investigated abiotic soil parameters (Fig. 7.5) at the depth of the pipes (indicated as “Zone with pipes” on the graphs). No significant increase in clay content or bulk density was observed just below the depth of the pipe (Fig. 7.5a, b). The soil texture of the profiles was silt loam (USDA-classification) until at least one meter below the pipe. The vertical penetration resistance (measured with an automatic penetrologger) revealed no significant increase directly below the depth of the pipes (Fig. 7.5c). In three profiles (RO5-1, RO5-2 and KL1) the vertical penetration resistance increased around 30 cm below the depth of the pipe. A decrease in horizontal penetration resistance was observed around a depth of 10 cm above the pipe (RO5-1, KL9) or at the depth of the pipe (KL1), but in one profile (RO5-2) no decrease was observed (Fig. 7.5d). Only site KL1 (pipe depth 70 cm) has a decrease in K_{sat} just above the depth of the pipe (Fig. 7.5e). At this site, the soil was reduced from a depth of 80 cm (groundwatergley). At the other three sites with CP, K_{sat} was already very low at more shallow depths than the depth of the pipe. No differences in abiotic soil properties with the other sites (pastures without piping, arable land and forest) can explain the preference of piping in the pastures with CP (Fig. 7.6). The results for clay content, bulk density and soil resistance are rather similar for all studied sites, except for the forest sites. The presence of a fragipan in one of the two forest soils explains the higher bulk density and soil resistance starting from 70 cm depth downwards. Throughout all soil profiles, the saturated hydraulic conductivity was generally low (median of 0.12 mm h^{-1} and 0.23 mm h^{-1} for all pastures with and without CP respectively) but it was highly variable. The high variation with locally very high K_{sat} values (maximum 275, 174 and 1710 mm/h for pasture, arable land and forest respectively) are explained by macropore flow due to the presence of biopores (e.g. earthworm channels).

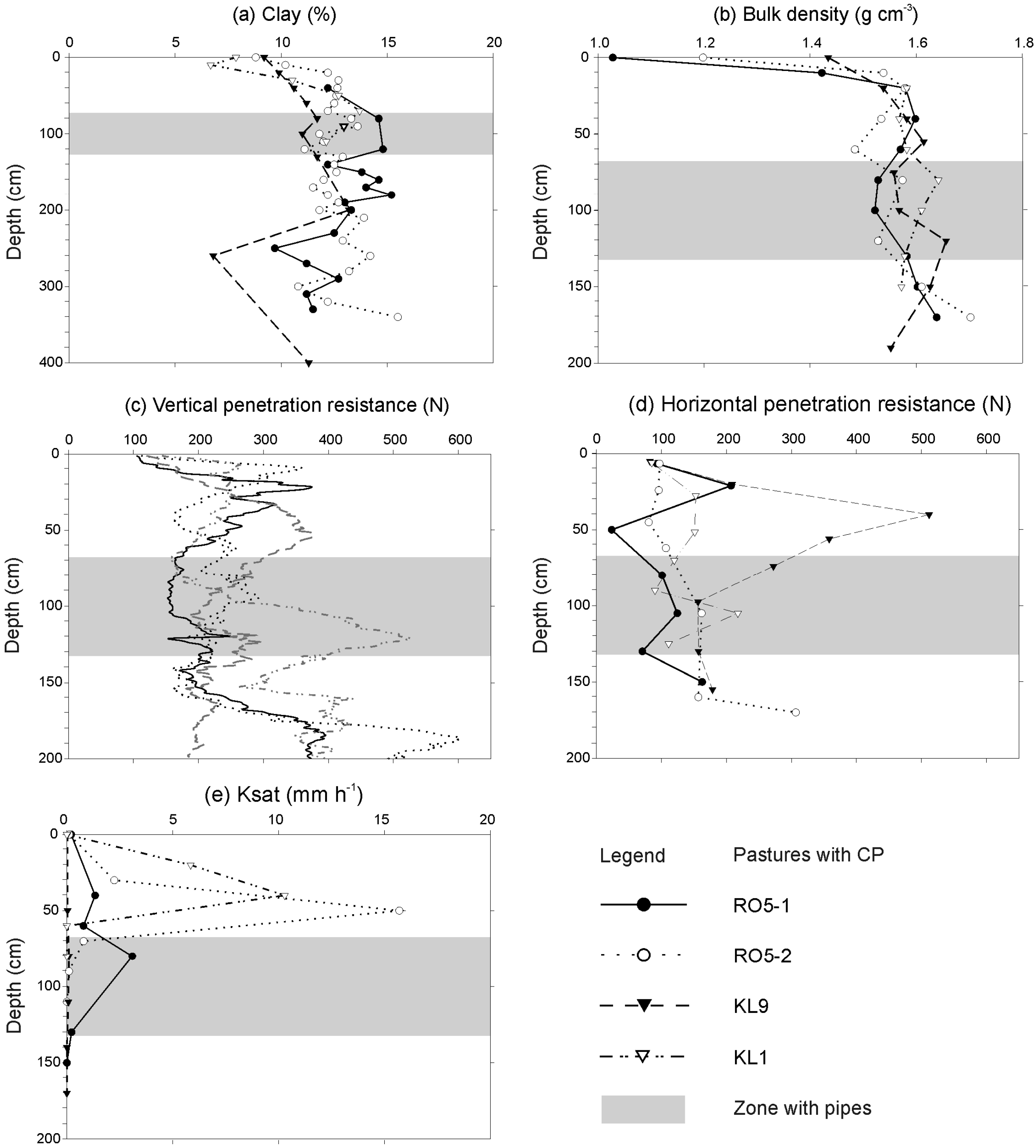


Fig. 7.5. Variation of soil property values with depth in soil profiles below four pastures with collapsed pipes (CP): (a) clay content until 400 cm, (b) bulk density, (c) vertical soil penetration resistance, (d) horizontal soil penetration resistance and (e) K_{sat} until 200 cm with indication of horizons having pipes. See Fig. 7.1 for location of the measuring sites (RO5-1, RO5-2, KL1 and KL9).

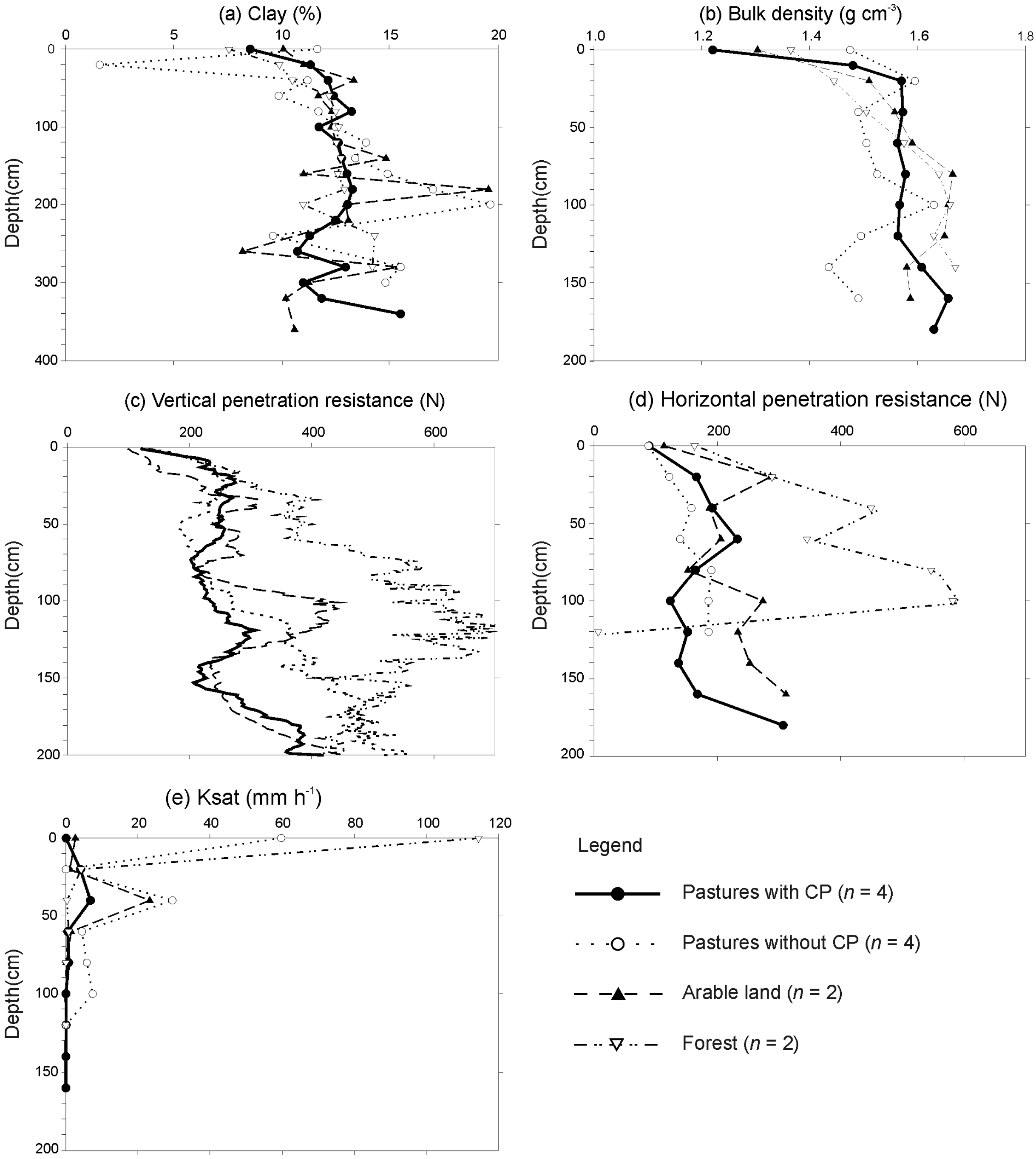


Fig. 7.6. Variation of mean soil property values with depth in soil profiles with and without collapsed pipes (CP) under pasture, arable land and forest: (a) clay content until 400 cm, (b) bulk density, (c) vertical soil penetration resistance, (d) horizontal soil penetration resistance and (e) K_{sat} until 200 cm for all studied sites (average for each land use). See Fig. 7.1 for location of the measuring sites. CP is collapsed pipes.

Fig. 7.7 shows the total number of earthworm channels and mole burrows per m² at different depths in the soil profiles in pastures with CP. The total number includes both the open and closed (filled with soil material and/or excretions) earthworm channels and mole burrows that were counted in horizontal soil cross sections of 1 m² (Fig. 7.2b). The profiles under pasture had the highest density of earthworm channels and mole burrows compared to forest and arable land (Fig. 7.8). The results were grouped in 3 soil depth classes for statistical analysis (non-parametric Wilcoxon test; R software), shown in Fig. 7.9. At soil depths of 80-120 cm, the biological activity expressed by the earthworm channel density for pastures with CP (mean 344 per m^2, max 582 per m^2) was higher than for pastures without CP (mean 128 per m^2), and significantly higher than for arable land and forest (mean 41 and 0 per m^2 respectively). At smaller soil depths (40-80 cm), earthworm activity was only significantly lower for forest (mean 38 per m^2) compared to all pastures (mean 335 per m^2). At larger depths (120-180 cm), no earthworm channels were observed for arable land and forest, and only a few were observed for pastures without CP (mean 23 per m^2) which is in clear contrast with the pastures with CP (mean 264 per m^2). Although studied on a relatively small horizontal surface area (1 m^2), the same trend was observed for mole burrows. There is a significant correlation between the abundance of earthworm channels and mole burrows (p < 0.05).

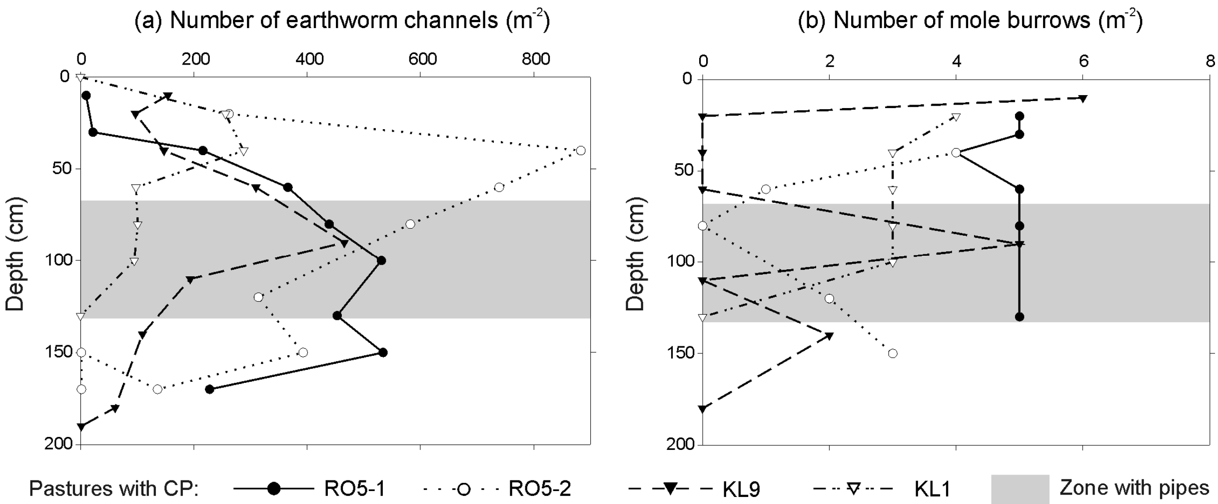


Fig. 7.7. Variation of biological activity with soil depth for pastures with collapsed pipes (CP) resulting from earthworms (open and closed earthworm channels; left) and moles (open and closed mole burrows, right), with indication of horizon having pipes. See Fig. 7.1 for location of the measuring sites (RO5-1, RO5-2, KL1 and KL9).

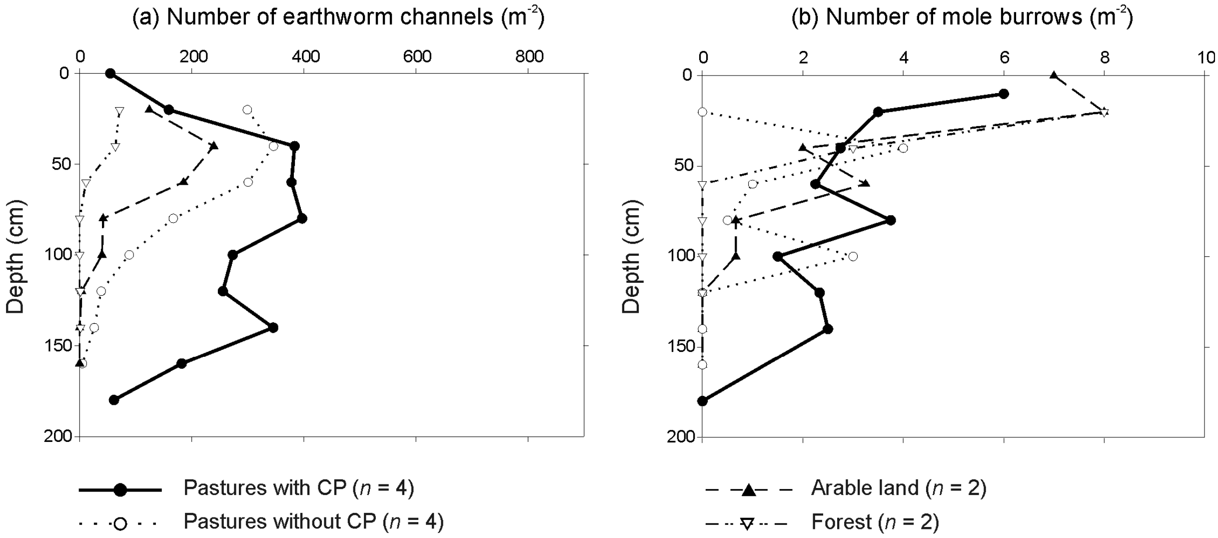


Fig. 7.8. Variation of biological activity with soil depth for all studied sites (average for each land use) resulting from earthworms (open and closed earthworm channels; left) and moles (open and closed mole burrows, right). See Fig. 7.1 for location of the measuring sites.

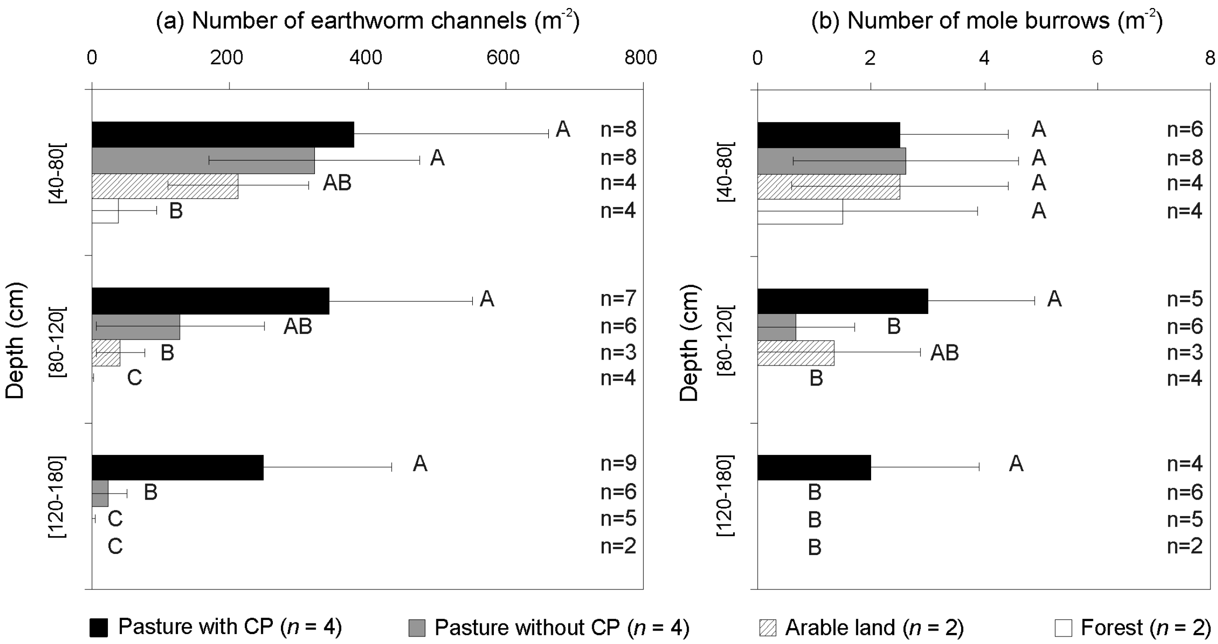


Fig. 7.9. Relation between land use and biological activity resulting from earthworms (open and closed earthworm channels; left) and moles (open and closed mole burrows; right) at different soil depths. Error bars indicate mean ± standard deviation; Means with a different letter differ significantly according to non-parametric Wilcoxon test at p < 0.05; n = number of 1 m² horizontal soil cross sections studied. CP is collapsed pipes.

7.3.2. Hydrological parameterization and Tertiary substrate of the augerings

Data of the WWT, both the observations for mottling (September-October 2009) and for groundwatergley (March 2010), the SWT and FZ are presented in box plots (Fig. 7.10). Statistical data are showed in Table 7.3.

Overall, mottling starts significantly deeper in pastures without CP than in pastures with CP (Fig. 7.10a). The differences are also significant when looking separately to the upslope sites, but not for the downslope sites. At the upslope position, the WWT (groundwatergley) seems to be located at larger depths in pastures with CP, while the opposite trend is observed for the WWT at downslope positions (Fig. 7.10b). These trends were not significantly different according to the statistical tests, however, these tests can not correctly take into account the sites where the WWT is deeper than 3 m (7% of the augerings). For both upslope and downslope sites, the SWT is deeper in pastures without CP (Fig. 7.10c). Although no significant differences can be detected because of the large variability in the data, a clear trend is visible. In 50% of the augerings in pastures without CP, the SWT is not found within 3 m soil depth, for both upslope and downslope sites. This is less for pastures with CP (27% and 7% for upslope and downslope respectively).

The expected negative correlation between the depth to the WWT or SWT and A was not observed ($p > 0.05$). The FZ is larger for pastures without CP (Fig. 7.10d). This difference is significant when considering the mean values, but not for the medians. Because for augerings where the groundwater table is at a depth larger than 3 m the groundwater table is set at 305 cm, augerings where both SWT and WWT are at depths larger than 3 m result in a FZ of 0 cm. This is obviously not correct, water can still fluctuate but this could not be noticed during the augerings.

There is no significant difference in the depth to the Tertiary substrate for pastures with CP compared to pastures without CP (Fig. 7.11a). It should however be emphasized that the substrate was not found within 3 m in ca. half of the augerings (49%).

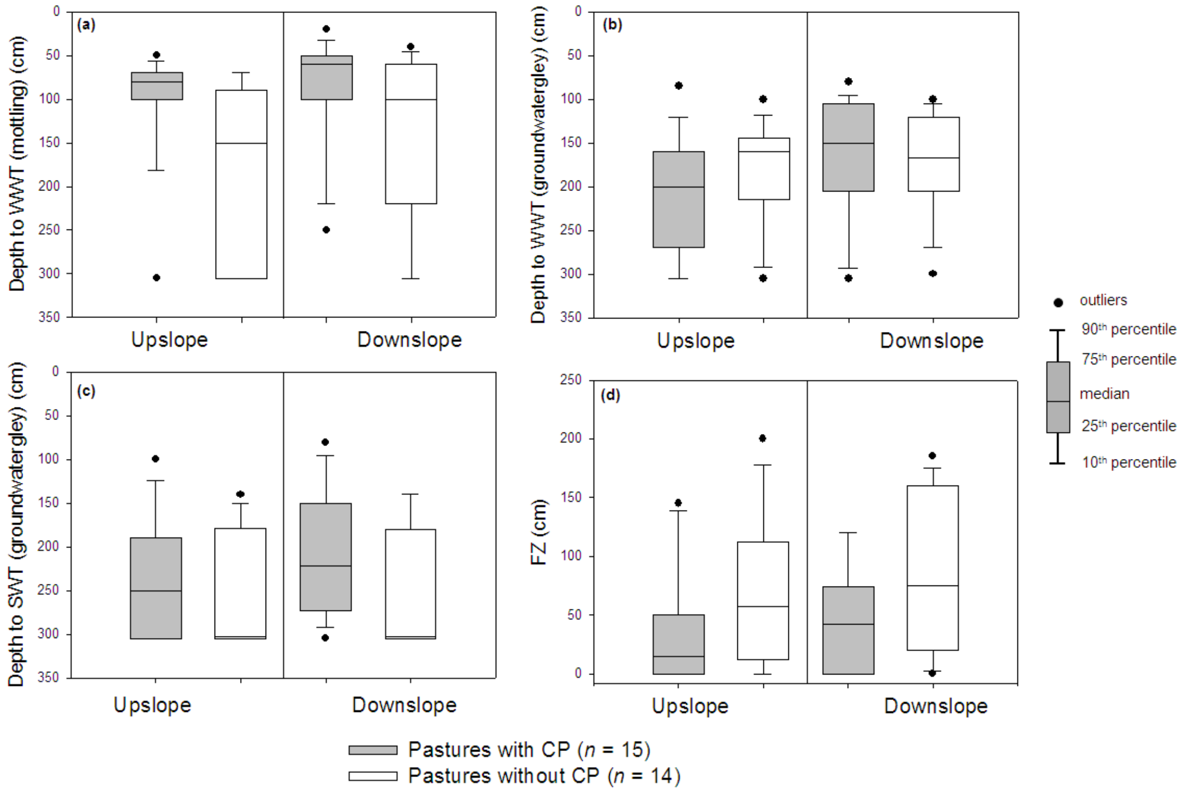


Fig. 7.10. Depth to winter water table (WWT (mottling) and WWT (groundwatergley)), the summer water table (SWT) and the disparity between SWT and WWT (groundwatergley) (FZ, fluctuation zone) for pastures with and without collapsed pipes (CP). Upslope and downslope refers to the most upslope and most downslope located measuring site within a parcel respectively.

Table 7.3. Statistical tests comparing the mean and median depth to the winter water table (WWT, based on mottling or groundwatergley), depth to the summer water table (SWT (groundwatergley)), the groundwater fluctuation zone (FZ) and the depth to the substrate for pastures with and without collapsed pipes (CP).

(cm)	dataset	t-test for means: p-value	nonparametric test for medians: p-value
depth to WWT (mottling)	all	0.001 *	0.008 *
	upslope [1]	0.005 *	0.027 *
	downslope [2]	0.100	0.065
depth to WWT (groundwatergley)	all	0.514	0.445
	upslope	0.354	0.272
	downslope	0.977	0.706
depth to SWT (groundwatergley)	all	N.A.	0.088
	upslope	N.A.	0.466
	downslope	N.A.	0.257
FZ	all	0.017 *	0.230
	upslope	0.118	0.466
	downslope	0.087	0.560
depth to Tertiary substrate	all	0.132	0.162
	upslope	0.152	0.450
	downslope	0.587	0.428

Significant differences between pastures with and without CP at $p < 0.05$ are indicated by an *. [1] Upslope positions: near most upslope CP or similar location in pastures without CP; [2] Downslope positions: near most downslope CP or similar location in pastures without CP. N.A. = not applicable.

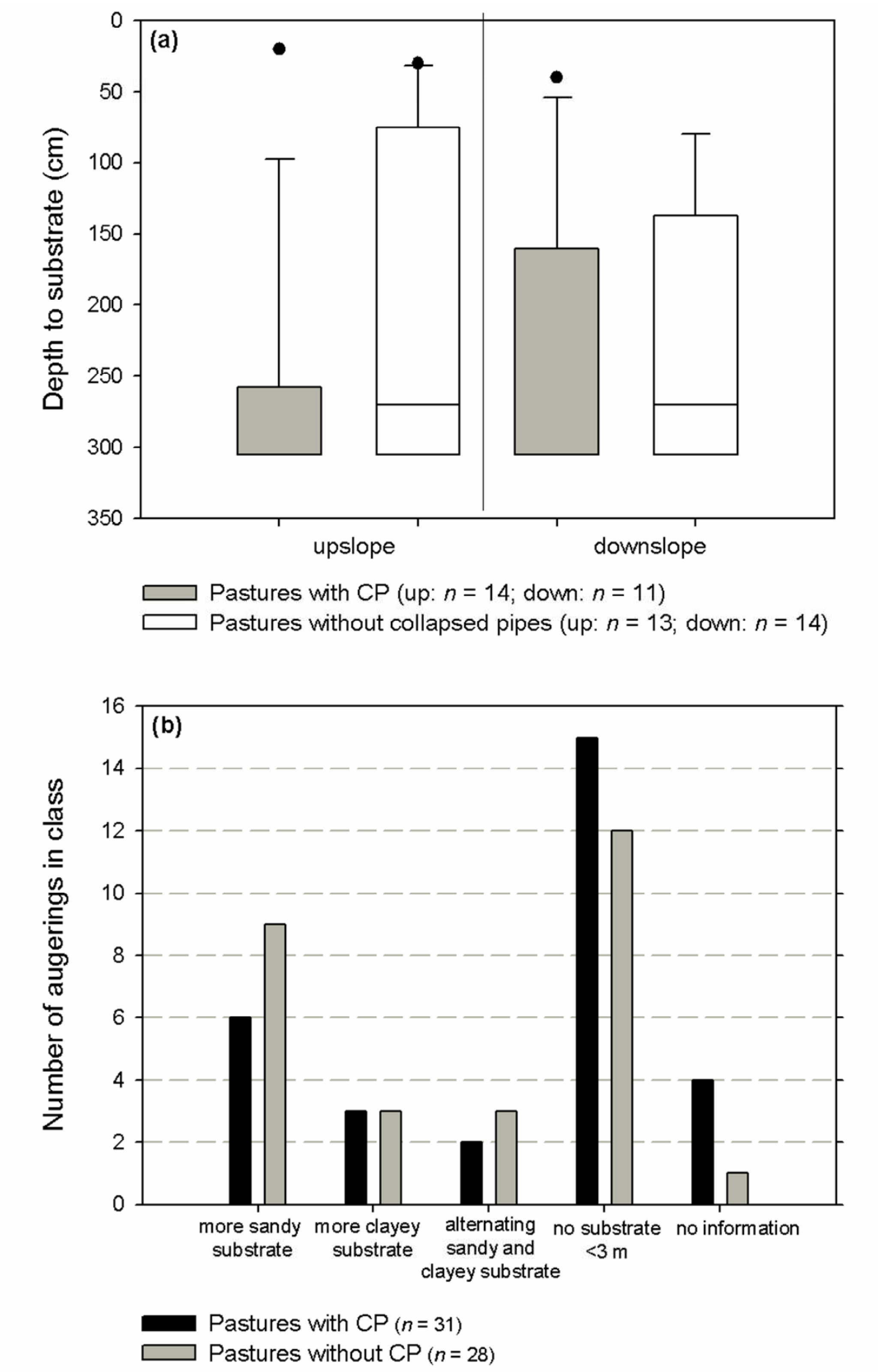


Fig. 7.11. Effect of the substrate (Tertiary lithology) on pipe collapse (CP): (a) depth to substrate and (b) texture of the substrate for pastures with and without CP, grouped into 5 classes: 1. More sandy substrate = sandy loam, loamy sand, loam; 2. More clayey substrate = silty clay loam; 3. Alternating sandy and clayey substrate; 4. No substrate < 3 m: augerings where substrate is deeper than 3 m; 5. No information: sites where augering is stopped before 3 m depth due to the occurrence of a hard layer or the water table.

7.3.3. Land use history

Between 1777 and 2006, the percentage of the studied parcels (i.e. farmer's plots; n_{total} = 168) under pasture increases steadily from 12% for parcels with currently CP and 13% for parcels without currently CP on the Ferraris map from 1777 to 100%. Fig. 7.12 gives the cumulative percentage of parcels under pasture since each time slot represented by each map, i.e. the number of parcels on each map that are pasture since that time and stayed pasture ever since. There is a significant increase of pastures between 1884 and 1950 and between 1963 and 1977, both for parcels with and without CP. The trends for parcels with and without CP are the same. At the time of the oldest historical map (i.e. 1777), the distribution of arable land and forest is different for the parcels with CP (35% arable land, 51% forest) compared to those without CP (50% arable land, 32% forest), but this difference disappears from 1824 onwards. Since 1995, 99% of the parcels with CP and 100% of the parcels without CP are pasture.

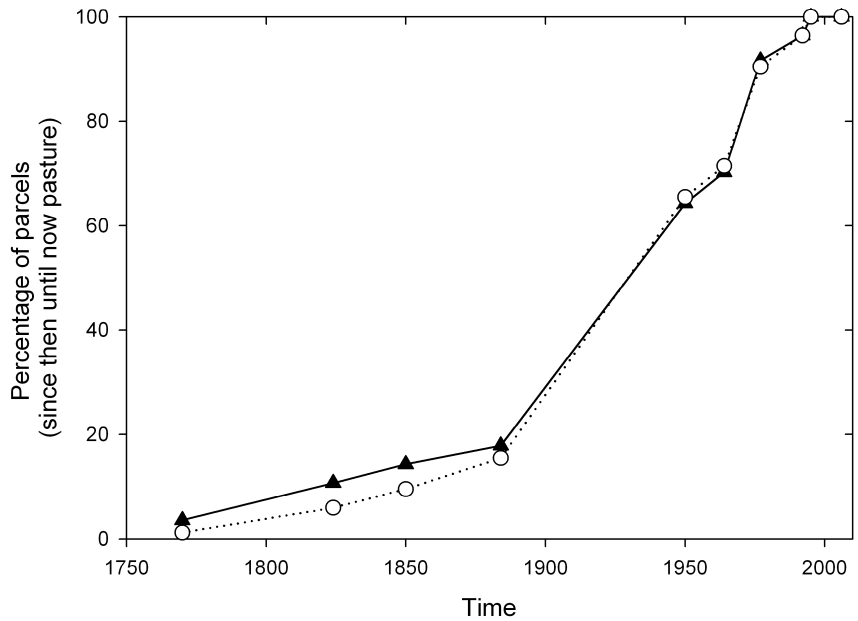


Fig. 7.12. Evolution of cumulative percentage of studied parcels under pasture since each year for which historical maps were available (See Table 7.1). CP is collapsed pipes.

7.4. DISCUSSION

7.4.1. Absence of duplex structure in soil profiles

Several authors report a 'duplex' structure as one of the requisites for piping development (e.g. Imeson and Kwaad, 1980; Imeson, 1986; López Bermúdez and Romero Díaz, 1989; Faulkner, 2006). Therefore, the first part of this research focussed on the question: is there a less permeable and more resistant horizon which may induce water stagnation and lateral flow in the pastures with CP? If such a more resistant horizon was present, it should be noticeable as discontinuities in soil property values such as texture, bulk density, soil resistance or K_{sat}. No such clear discontinuities were observed in the present study at the depth of the soil pipe, although investigated for a limited number of profile pits. The question arose whether other differences in these abiotic soil properties could be observed when comparing the pastures with CP with the other studied sites (pastures without CP, arable land and forest). However, no significant differences in abiotic soil properties under the other land uses can explain the preference of pipe collapse in the pastures with CP either.

Soils derived from loess, with a high percentage of silt like the studied profiles, are known to be susceptible to piping (e.g. Laffan and Cutler, 1977; Jones, 1981; Faulkner, 2006). The typical texture of the soil horizons with soil pipes was silt loam with an average grain-size distribution of 11.5 % clay, 72.7% silt and 15.6% sand (Table 7.4). None of the sampled horizons contained $CaCO_3$. These horizons are therefore comparable to decalcified loess (C_1; see Chapter 2 section 2.2) or possibly colluvium. Calcareous loess was not observed in the soil profiles. The high susceptibility of decalcified loess to piping was demonstrated using the pinhole test in Chapter 2.

Table 7.4. Texture and $CaCO_3$ content of the soil horizons with pipes.

Soil horizons	% Clay (0-2 µm)	% Silt (2-63 µm)	% Fine sand (63-200 µm)	% Coarse sand (>200 µm)	$CaCO_3$ (%)
RO5-P1	11.8	67	20.8	0.4	0
RO5-P2	10.8	73.9	14.9	0.4	0
KL9	11.3	71.1	16.4	1.2	0
KL1	12.3	78.9	8.4	0.1	0
mean	11.5	72.7	15.1	0.5	0

Although Chapter 4 showed the importance of a clay-rich substrate while studying the distribution of CP in the area, such clay layers were not found directly under the pipe. Soil profile pits were dug near the lowermost CP, sites with a large depth of colluvium. Upslope of the CP, however, a clay-rich substrate or hard impermeable layer was found at more shallow depths (< 1 m in two of the four pastures) causing springs and the necessary water supply. During the soil augering campaign, the depth of the substrate was not found to be significantly different in pastures with CP compared to pastures without CP, but a sandy substrate was more often observed in the pastures without CP.

Another hypothesis to be tested was that lateral flow would be enhanced at depths where vertical penetration resistance increases just below the pipes or the horizontal resistance decreases at the depth of the pipe. No compact layer (as would be indicated by an increased bulk density or vertical penetration resistance) was observed directly below the pipes, although some soil profiles showed an increase in vertical penetration resistance around 30 cm below the pipes. Even larger increases in bulk density or vertical penetration resistance were however observed in pastures without CP, so this could not explain the occurrence of the pipes. In some cases, a decrease in horizontal penetration resistance was observed at the depth of the pipe, but there was no general trend. It could be assumed that K_{sat} decreases at the depth of the pipe, but it was observed that K_{sat} is generally very low (already at more shallow depths than the depth of the pipe). The K_{sat} values were very variable, with the highest values where more earthworm channels occurred. Higher infiltration rates through earthworm channels can enhance the transport of water to deeper soil layers (e.g. Ehlers, 1975; Ligthart, 1996; Botschek et al., 2002a).

7.4.2. The effect of biological activity on infiltration and piping

Pasture, the land use where almost all CP were observed in the study area (Chapter 4), is the land use with the highest density of earthworm channels and mole burrows (depth 50-180 cm) compared to forest and arable land. This effect of land use on earthworms had been reported in literature before. In pastures, the number of earthworms is higher than on parcels with other land use due to high availability of organic matter (Edwards and Bohlen, 1996), as earthworms prefer to feed on soft grass and dung (Funmilayo, 1977). Tillage can significantly reduce the number of burrows and macropores that transmit water to the groundwater (Chan and Heenan, 1993; Friend and Chan, 1995). In Central-Belgium, the earthworm channels have an average diameter of 6 mm and can reach a depth of 80-120 cm (Langohr and Crombé, 1999). The presence of moles is related to the abundance of earthworms, being their major food (Funmilayo, 1977; Gorman and Stone, 1990). Because it is not possible to obtain accurate data on mole burrows from 1 m² plots (often no burrows were observed), this study mainly focussed on the presence of earthworm channels. Nevertheless, a similar trend could be observed for mole burrows as well. A high biological activity seems to be important for the occurrence of CP, as this is the main difference between the different land uses and between the pastures with and without CP, especially at the depths where soil pipes occur. Chappell (2010), citing Dunne (1990 p. 29) and Vieira and Fernandes (2004), reported that the exact location of pipes within zones of subsurface convergence is probably related to the local spatial variability in K_{sat}. The present study confirms that earthworm channels can cause these local differences in K_{sat}. Earthworm activity of anecic species (*L. terrestris* L.) favours rapid vertical infiltration through macropore flow whereas mole burrows may favour lateral flow in the soil profile (during rising water tables) which may lead to piping because of biopore flow velocity being larger than matrix flow velocity. The deep vertical burrows of anecic earthworm species (*L. terrestris* L.) enhance the macroporosity with 20-100% and the hydraulic conductivity with 80% (Gobat et al., 2004). Similar to our field observations, Bouma et al. (1982) showed high infiltration rates in earthworm channels which ended in mole burrows. Because of the rapid downward flow in the mole burrow, these channels were difficult to fill with water and infiltration could continue. Other authors pointed to the role of animal burrows in the formation of pipes as well, mostly from earthworm and moles (e.g. Botschek et al., 2002a) or gophers (e.g. Carroll, 1949). Without concerning piping, gopher burrowing activity appeared to have no effect on infiltration rates in a prairie landscape in Alberta, Canada (Zaitlin et al., 2007). In earth grassland in the UK, Holden and Gell (2009) found that infiltration significantly increased with leatherjacket (cranefly larvae) burrow density.

7.4.3. Effect of groundwater table position on pipe formation

The measurements of the soil characteristics including biological activity could only be made for 12 profiles, of which 8 in pastures. Counting earthworm channels is not easily extended to larger scales but, because it is noticed that the groundwater table level set the limit to the depth of the vertical burrows of *L. terrestris* L. (Hoogerkamp et al., 1983; Nuutinen and Butt, 2003), we focussed on studying the relation between groundwater table positions and CP and linking this to the observations of biological activity. Furthermore, while the study of the soil profiles concentrated on sites with a similar geology, the investigation of the groundwater table is now extended to 29 sites with a similar topographical situation to exclude the influence of the different hydraulic conditions related to differences in A.

Mottling, indicating the highest position the groundwater table has ever been for several days, can be taken indicative of the initial conditions (before piping initiation), while the WWT (groundwatergley) was the actual groundwater table that we observed at the end of the winter and, thus, at a moment when piping was already active. The highest position of the groundwater table (indicated by mottling) was higher in pastures with CP and the groundwater table has never reached that level in pastures without CP. It is possible that in pastures with CP the WWT was high at the moment of the initiation of the piping process. After the formation of pipes, the groundwater table then dropped because the water is drained by the pipes. For the actual WWT (groundwatergley), the difference between pastures with and without CP is smaller and not significant. Nevertheless, the downslope average WWT is deeper at sites without CP, while the upslope average WWT is deeper at sites with CP. These small differences could be due to the fact that at the upslope sites in pastures with CP the pipes can act as natural drainage channels and lower the groundwater table. At the downslope sites, the slope is less steep and the drainage effect of the pipe will be negligible. Based on field observations, it can be assumed that most pipes end in feeding the groundwater table which could also contribute to rising levels of the WWT in some cases. The results on the SWT positions show that at least during a part of the year (summer), the groundwater table is at deeper positions in pastures without CP, where the SWT was more than 3m below the soil surface in 50% of the observations.

The larger extent of the FZ in pastures without CP indicates a different regime of the groundwater table compared to pastures with CP. In pastures with CP, the groundwater table is always high, while in pastures without CP, the SWT is deeper. This means that pastures with CP have a more stable groundwater table and, consequently, are always rather wet. These conditions define an attractive environment for biological activity. The influence of biological activity on piping, in relation to the depth of the groundwater table, will be discussed in paragraph 4.4. Heede (1971) suggested that the change from vertical to horizontal directions in pipes can be related to groundwater table variability, but this applies only when the groundwater table is not very deep, which has been observed in our pastures with CP. When the SWT is deeper, like in pastures without CP, it takes time for the groundwater table to reach the same position as in pastures without CP. Another factor which may influence the hydrological state of the pastures is artificial drainage, which can lower the groundwater table. Unfortunately, this information is only rarely available for pastures in the study area.

7.4.4. Interaction between biological activity, groundwater level and piping

Earthworms move to deeper soil horizons because they dislike a cold or dry surface soil (Edwards and Bohlen, 1996). In this study, the SWT is observed at more shallow depth in pastures with CP. Even in summer, the groundwater table is not too deep in these pastures, so the earthworms can migrate deeper. The pastures with CP have the highest earthworm channel density in the FZ between SWT and WWT. In pastures without CP, however, the SWT is deeper. The median depth of the SWT in pastures without CP is more than 3 m, deeper than the deepest anecic species of earthworms observed in soils within this study. For the 8 pastures where the biological activity was studied, more earthworm channels and more mole burrows were observed below the WWT. This implies that if the groundwater table rises in winter, these mole channels are submerged and the flowing water can entrain material which leads to the formation of pipes. Even though macropores might not always be directly connected, they apparently become effectively connected (e.g. by loose soil, decaying organic material) when moisture levels are high enough to be favourable (Noguchi et al., 1999). In fact, macropores are often found to transmit soil water while the surrounding soil matrix is not saturated, indicating hydraulic discontinuities (Cammeraat, 1992). This process of increasing water saturation leading to eventual subsurface water flow is a process of self-organization (Nieber et al., 2006). The rising groundwater table during autumn and winter coincides with the period in which both earthworms and moles are the most active (Evans and Guild, 1947; Edwards and Bohlen, 1996; Edwards et al., 1999). If the SWT is less deep, the groundwater table reaches the zone with high biological activity relatively fast, resulting in a longer time period with saturated conditions in this zone. Therefore, the probability of inducing piping erosion and CP will be higher in soils with shallow SWT compared to a situation with a deeper SWT, where groundwater is only present at shallow depths during a short time period.

The field data collected suggest the following conceptual model of soil profiles under different land use with and without CP in the study area (Fig. 7.13). The figure indicates that biological activity and the summer groundwater table levels in the soil profiles partly explain the difference in susceptibility to soil piping. The pastures with CP had a higher biological activity in the FZ (between SWT and WWT) compared to the pastures without CP. It can therefore be hypothesized that piping in the studied loess area is triggered by high temporary groundwater tables in combination with macropores induced by biological activity (earthworms, moles) in pastures if other conditions in terms of topography and lithology are met. Although no textural discontinuity was observed at the depth of the pipes, the deeper clayey substrate below the loess layer may have an indirect influence by creating temporary groundwater tables and springs on hillslopes. It should, however, be mentioned, that the interaction between biological activity and the occurrence of pipes works in both ways. The macropores enhance pipe flow (and possibly initiate piping erosion), but as the pipe can act as a drain for water, this positively affects the presence of earthworms (Nuutinen and Butt, 2003). The lowered groundwater table level near the drains provides an attractive environment for the population growth of the earthworms. More earthworm channels near the pipes enhance again the supply of water to the pipe and therefore also the risk for piping erosion. Also moles tend to concentrate near the sides of drainage lines (Funmilayo, 1977).

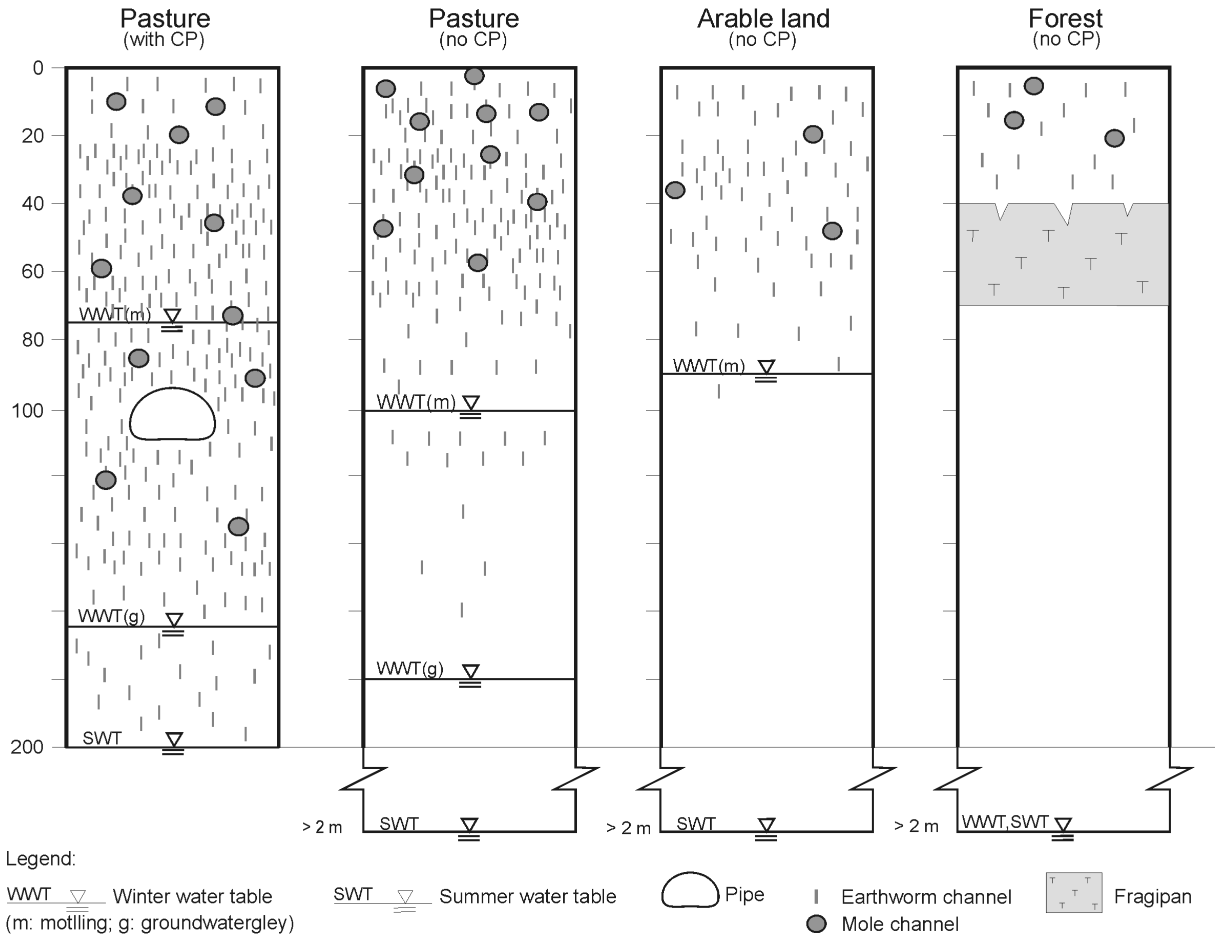


Fig. 7.13. A conceptual model of soil profiles under different land use with and without collapsed pipes (CP), based on field observations, indicating the intensity of biological activity, the presence or absence of pipes and the position of the winter and summer water table.

As forest implies a higher evapotranspiration compared to cropland and pasture (Verstraeten et al., 2005), land use change from forest to pasture will decrease the depth to the groundwater table and therefore possibly the risk for piping erosion. Model simulations by Batelaan et al. (2007) indicated that the difference of average yearly groundwater recharge between forest and pastures is 50.7 mm, resulting in difference in groundwater table depth of 12.7 cm (soil porosity of 0.4; Table 7.5). Hence, the water table increase after conversion from forest to pasture will still be smaller than the differences in SWT and WWT observed in the soil profiles, with limited consequences for pipe development.

Table 7.5. Effect of land use on groundwater recharge in Flanders (after Batelaan et al., 2007)

	average grondwater recharge (mm)			difference to pasture in soil depth (cm)		
	yearly	summer	winter	yearly	summer	winter
Pasture	243.5	-3.2	246.7			
Cropland	224.6	-12.0	233.6	-4.7	-2.2	-3.3
Forest	294.2	38.6	255.6	12.7	10.4	2.2

7.4.5. Land use history

If piping is triggered by intense biological activity, it could be hypothesized that a certain transition period is needed after the conversion of forest or agricultural land to pasture before the biological activity is sufficiently high to trigger piping erosion. However, 99% of the parcels with CP and 100% of the parcels without CP turned out to be pasture since 1995 (12 years according to reference year 2007, start of field survey), so the age of the pasture can not explain the difference in piping occurrence. Moreover, several studies report that the biological activity increases fast when land use changes to pasture (Ligthart and Peek, 1997; van Eekeren et al., 2008). Ligthart and Peek (1997) showed that after inoculation of a pasture in the Netherlands with different earthworm species, these earthworms dispersed with an average horizontal velocity of 6.3 m yr^{-1}. The anecic species *L. terrestris* spread more slowly, but yearly rates may have been underestimated because earthworms were only collected over a soil depth of 30 cm and anecic species have deeper burrows. After 7 years, the earthworms had migrated over a horizontal distance of approximately 45-46 m. The abundance of earthworms peaked at 4.1 years, after which it dropped to a lower level, but the burrow system continued to deepen after the maximum density had been reached. In a 36 years old experiment on a sandy loam soil in Belgium, the biological activity in a permanent arable land, permanent grassland and a ley-arable crop rotation was compared (van Eekeren et al., 2008). In the three-year grass ley, the abundance of earthworms returned to the level of permanent grassland in the second year. For the biomass to reach similar levels to those in the permanent grassland, the ley period should last 4-5 years. Although the number of earthworms increased fast, the anecic species did not recover the initial dominance they had in the permanent grassland (38% and 52% respectively). If already 4-5 years after a land use change (from forest or cropland to pasture) the abundance of anecic earthworms is almost as high as in permanent grassland, piping erosion can already occur after a short time since land use change. The fact that the parcels with CP in 2007 had a higher percentage under forest in 1777 compared to the parcels without CP in 2007 could indicate that these parcels were less appropriate for cropland (e.g. too wet or too steep). The impact of this difference in land use history on susceptibility to pipe collapse is however limited, as this difference has already disappeared for almost 200 years. In other studies, however, land use or management did play a significant role in triggering piping erosion. Land management (moorland gripping, surface drainage) was reported to be the most important control on hillslope pipe frequency in blanket peats (Holden, 2005). Artificially drained blanket peat catchments had a significantly greater soil pipe density than intact catchments (Holden, 2006). Also in peat in the UK, Jones and Cottrell (2007) observed a marked reduction in the number and size of pipes after afforestation.

7.5. CONCLUSIONS

Unlike the expectations, no clear discontinuities in soil texture, saturated hydraulic conductivity, penetration resistance or bulk density were found at soil depths where soil pipes occurred in collapsible loess-derived soils in Belgium.. Pasture, the land use where almost all CP were observed, is the land use with the highest density of earthworm channels and mole burrows compared to forest and arable land. A high biological activity was found at larger soil depths in pastures with CP (at > 120 cm depth more than 200 earthworm channels per m² on average) than in pastures without CP (at > 120 cm depth few earthworm channels left). The analysis of groundwater levels for a larger dataset of pastures confirms that the rather stable groundwater levels in pastures with CP contribute to an attractive environment for earthworms and thus also for moles. The SWT stays at shallow depth and a larger number of macropores exists below the WWT. When the groundwater level rises again, these channels will easily fill up. In contrast, these mechanism will not be active in pastures without CP, because they had a deep SWT and no earthworm channels below the WWT. This reduces the chances of pipe formation in these pastures. Considering the fact that earthworm activity of anecic species favours rapid vertical infiltration and mole burrows favour lateral flow in the soil profile, it can be concluded that biological activity in combination with sufficiently high groundwater tables plays an important role in the development of soil pipes in the Flemish Ardennes in Belgium. It should be emphasized that these observations were obtained from a limited number of profile pits (n = 12) and augerings (n = 30), but the acquisition of the data needed to obtain absolute certainty is too time demanding. Furthermore, the results can not be easily extended to other regions with piping. No single factor or group of factors is universally responsible for the development of piping (Jones, 1981). The authors are aware that the factors controlling the initiation of pipes may vary with soil type, climate and other factors.

Finally, the hypothesis was tested that a transition period is needed after land use changes from forest or arable land to pasture to develop a sufficient number of biopores that would favour piping erosion. However, the age of pastures cannot explain the difference in piping occurrence, because also the parcels without CP are already pasture for a long time (objective (iii)). Almost all pastures are at least 12 years old and since various studies indicate that the increase in biological activity after land use change to pasture is very fast (i.e. 4-5 years), this period is probably long enough to create sufficient biopores that could favour piping erosion.

Chapter 8

Response of pipeflow to groundwater level and precipitation: case study site Kluisbergen

8.1. INTRODUCTION

One of the priorities in piping research should be the study of the efficiency of pipes in transferring sediment, water and solutes to the lower slopes and the stream channels (Bryan and Jones, 1997). Despite early pioneering investigations (e.g. Gilman and Newson, 1980; Jones and Crane, 1984; Bryan and Harvey, 1985; Walsh and Howells, 1988), Bryan and Jones (1997) identify the lack of measurements as one of the major problems complicating assessment of the hydrological role of piping. Since their review, several studies attempted to close this gap and to confirm the importance of pipeflow to runoff generation in a wide range of environments (e.g. Uchida et al., 2001; Noguchi et al., 2001; Holden and Burt, 2002). The runoff characteristics of pipeflow and its effect on hydrological processes in forested hillslopes in Japan were extensively studied (Uchida et al., 1999; 2001; 2005). In loess in China, the water and sediment delivery was monitored at six tunnel outlets for 15 events in a period of 10 years (Zhu, 1997; Zhu et al., 2002). The tunnel discharge showed an erratic relation to rainfall, due to the instability of the tunnel system. To conclude, observations ranging from the UK (Jones, 1987a) to Canada (Bryan and Harvey, 1985), India (Putty and Prasad, 2000), Japan and China (mentioned before) suggest that pipeflow can be a significant contributor to streamflow in many headwater basins (Jones, 2010). Jones's review has demonstrated that soil pipes may generally contribute up to nearly 50% of the stormwater discharge, although the contributions can vary widely (10-72%; Bryan and Jones, 1997). In one particular catchment in the UK, the pipe network was responsible for doubling the dynamic contributing area (Jones, 1987a). However, pipes generally show an irregular behaviour, varying between storms, environments and between perennial and ephemeral channels even in the same catchment. For piping in loess-derived soils in temperate humid climates, only one soil pipe in Germany was monitored during one month (Botschek et al., 2000). Nevertheless, in landscapes with deep soils, high infiltration capacities and dense vegetation covers, most hillslope runoff reaches the stream channel as subsurface flow (Abrahams, 1980). Therefore, this chapter aims at contributing to a better understanding of the hydrological functioning of soil pipes by means of an explorative case study. The specific objective is to investigate the relation between pipeflow, rainfall and groundwater, and to determine the dominant source of the water flowing through the soil pipes in loess-derived soils in a temperate humid climate, by means of a hydrochemical and a hydrometric analysis. The hydrochemical analysis evaluates whether the composition of the pipeflow corresponds to ‘old’ pre-event water (groundwater) or if it is more similar to ‘new’ event water (rainfall), while the hydrometric analysis describes the response of the pipeflow and the water table to rainfall events.

8.2. MATERIALS AND METHODS

8.2.1. Study site

A small catchment (2.2 ha) with collapsed pipes was selected in the study area (Fig. 8.1 and Fig. 8.2). The study site KL1 (see also Chapter 7) has altitudes ranging from 60 m to 90 m a.s.l. and a mean slope gradient of 12.4% (4 - 29%). The Tertiary lithology consists of homogenous blue massive clays containing more than 50% of clay (Aalbeke Member; Tertiary geological map 1:50,000; AGIV, 2001a), covered by Quaternary loess. Weathering of the loess resulted in loamy soils. The soil map (1:20,000; AGIV, 2001b) indicates upslope sandy loam soils with argic or cambic horizons (LbB, Belgian Soil Classification) and downslope, sandy loam soils with gleyic colour patterns at shallow depth (50-80 cm; Ldp) which correspond respectively to Luvisols, Cambisols and Regosols in the World Reference Base soil classification system (IUSS Working Group WRB, 2007). Texture analysis of a profile at the study site revealed the following value ranges: 7-14% clay, 72-76% silt and 13-16% sand. A wet spot (near P1) with exfiltrating water in some periods of the year is visible in the upslope part of the pasture.

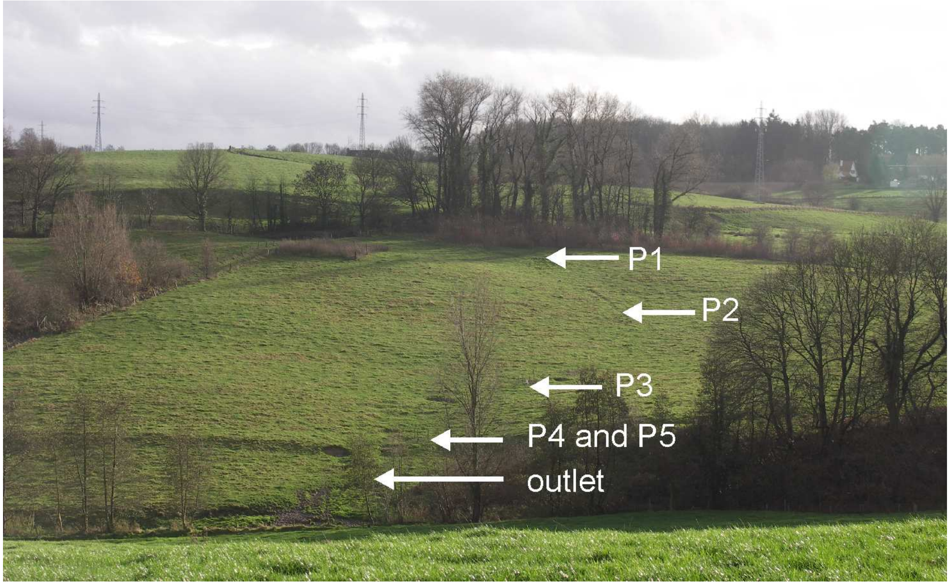


Fig. 8.1. View towards the south of the study site KL1 (Kluisbergen, December 2009; J. Poesen)

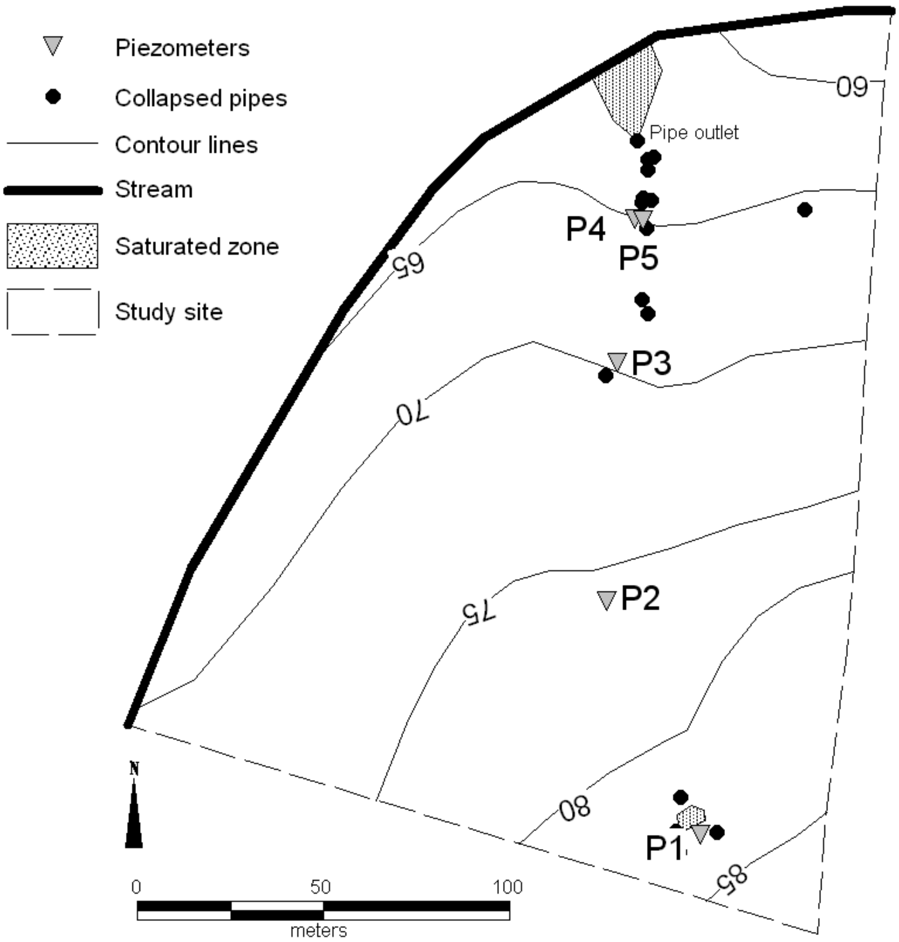


Fig. 8.2. Study site with indication of the collapsed pipes and piezometers.

8.2.2. Measurements of rainfall, groundwater and pipeflow

The pipe discharged onto the surface generating overland flow. At this outlet, a barrier with a V-notch weir was constructed and a digital water level recorder (Mini-Diver, Schlumberger, accuracy 0.05%/10m) was installed to measure the pipeflow discharge (February 2010). Five piezometers with similar dataloggers (P1 – P5; Fig. 8.2) were installed at 5 locations in the pasture, recording the groundwater table at 10 min interval. Atmospheric pressure was recorded as well to compensate for barometric pressure (Baro-Diver, Schlumberger). During the monitoring period February 2010 – April 2011, precipitation was measured with a rain gauge (0.2 mm tipping bucket) to obtain a 5 min data series (Tinytag count datalogger, DataLog, Aalst, Belgium).

Fig. 8.3. V-notch weir at the pipe outlet.

8.2.3. Chemical water analysis

At five different moments between 23 December 2010 – 12 April 2011, water samples of the hydrological compartments and flow paths in de study area were taken: rainfall, groundwater at five locations (piezometers P1 – P5), the downslope stream and the pipeflow itself. The hydrochemical analysis includes the measurement of the primary ions into the samples, the pH and the electrical conductivity (EC). The concentration of the main anions (Cl^-, SO_4^-, NO_3^-) were determined by ion chromatography (IC). The concentration of the main cations (Mg^{2+},

Ca^{2+}, K^+, Na^+ and Si^{4+}) were determined by Induced Coupled Plasma – Optical Emission Spectrometry (ICP–OES). The presence of (bi)carbonates was identified by gran titration. A Tukey t test was used to determine significant mean differences of concentrations, EC and pH at the 0.05 probability level ($p < 0.05$). Relative concentration composition was evaluated using Piper diagrams.

8.3. RESULTS

8.3.1. Response of pipeflow to rainfall events and groundwater fluctuations

During the measuring period, 152 rainfall events with intervals of at least 6 h and duration of more than 10 min were identified. Pipeflow discharge measured at the pipe outlet varied widely with an average of 0.27 l s^{-1} during the measuring period. The maximum value recorded was 3.6 l s^{-1} during the event of 13 November 2010 (duration of 46.1 h, intensity of 1.5 mm h^{-1} with periods of 24 mm h^{-1}) with an antecedent rainfall of 45.4 mm during the 5 preceding days (intensities exceeded 20 mm h^{-1}). The water reservoir with the V-notch sometimes suffered from sedimentation and was cleaned regularly after significant events. After the heavy event of November 2010, ca. 0.23 m^3 or 350 kg sediment had to be removed, the maximum observed during the measuring period. The evolution of a collapsed pipe during this period at the same site is reported in Chapter 3.

The measured pipe system was considered to be a perennial pipe, although for short periods (often less than 1 hour) no pipe discharge was recorded in July and August. Based on field observations in this drier period, we know that pipeflow discharge did not totally cease but became smaller than the threshold of the monitoring device. Fig. 8.4 and Fig. 8.5 show the typical response of pipeflow to rainfall events, as well as the corresponding groundwater table fluctuations in winter and summer.

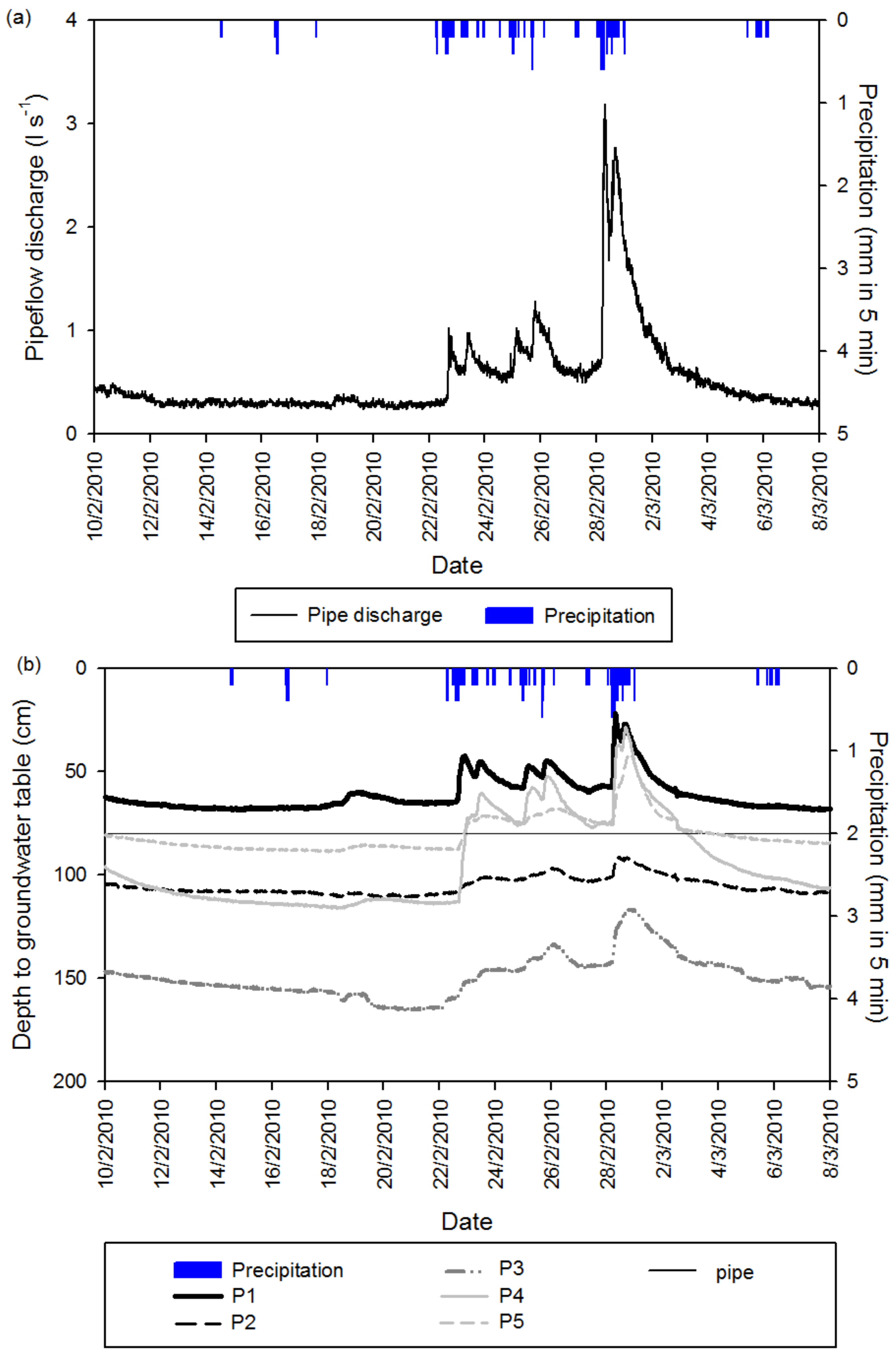


Fig. 8.4. (a) Pipeflow discharge (l s^{-1}), precipitation (mm), and (b) groundwater tables at the end of the winter of 2010.

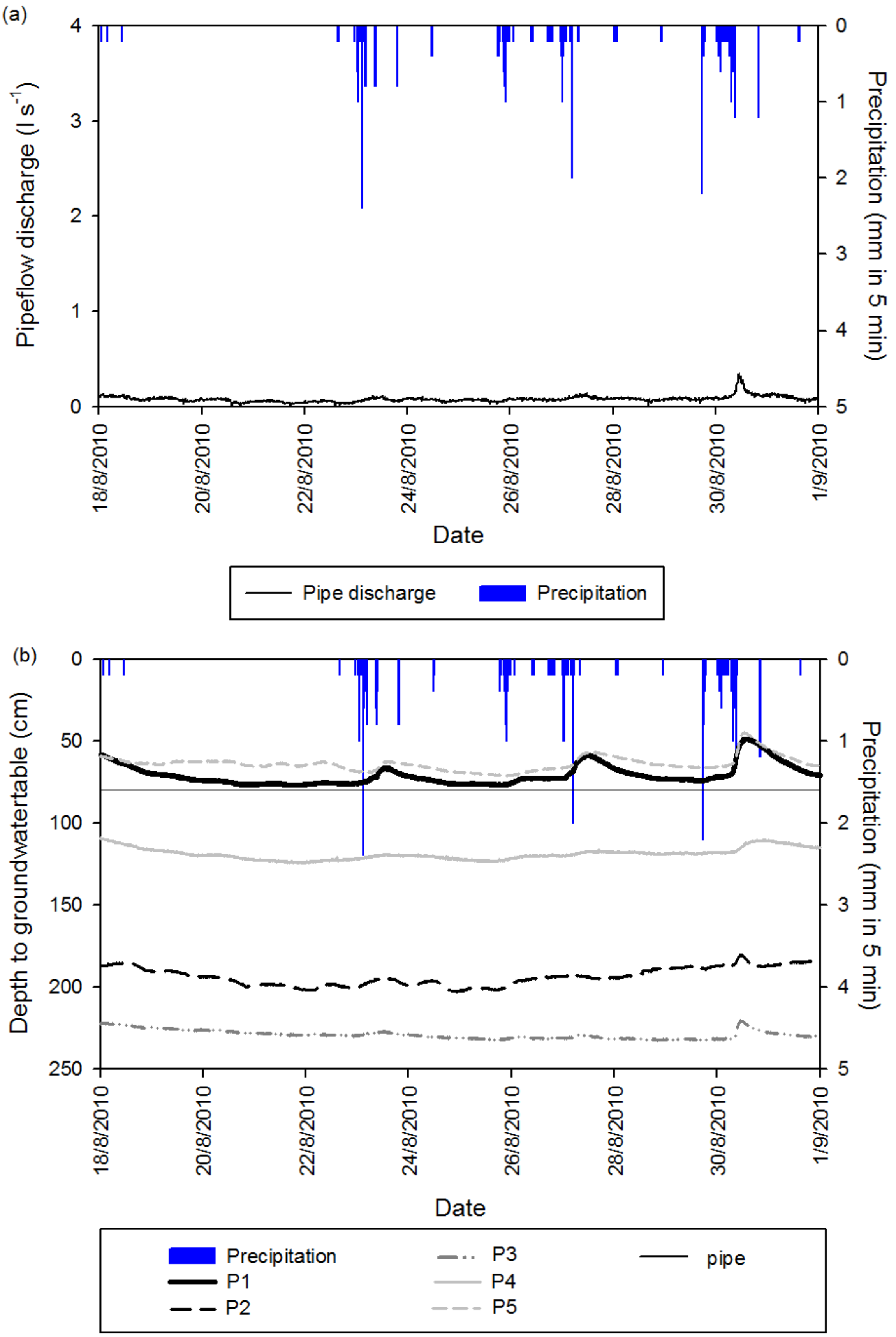


Fig. 8.5. (a) Pipeflow discharge (l s^{-1}), precipitation (mm), and (b) groundwater tables at the end of the summer of 2010.

The pipeflow discharge showed a significant response to 28% of the rainfall events with an average increase of 352% (range: 33 – 2093%) compared to the baseflow at that moment. When no clear hydrograph response was observed, but the pipeflow discharge increased with more than 30%, the response was considered as 'intermediate' (e.g. during the recession limb of a previous hydrograph). Based on the regression of the duration to the intensity of the different events, a threshold line below which no pipeflow response is expected could be identified parallel to the regression line (Fig. 8.6). There was no relation between preceding rainfall (2 or 5 days before the start of the event) and pipeflow response. Additionally, thresholds of rain duration and intensity were identified for summer and winter events separately in Fig. 8.7. Higher intensities or longer durations are necessary to create significant pipeflow response in summer.

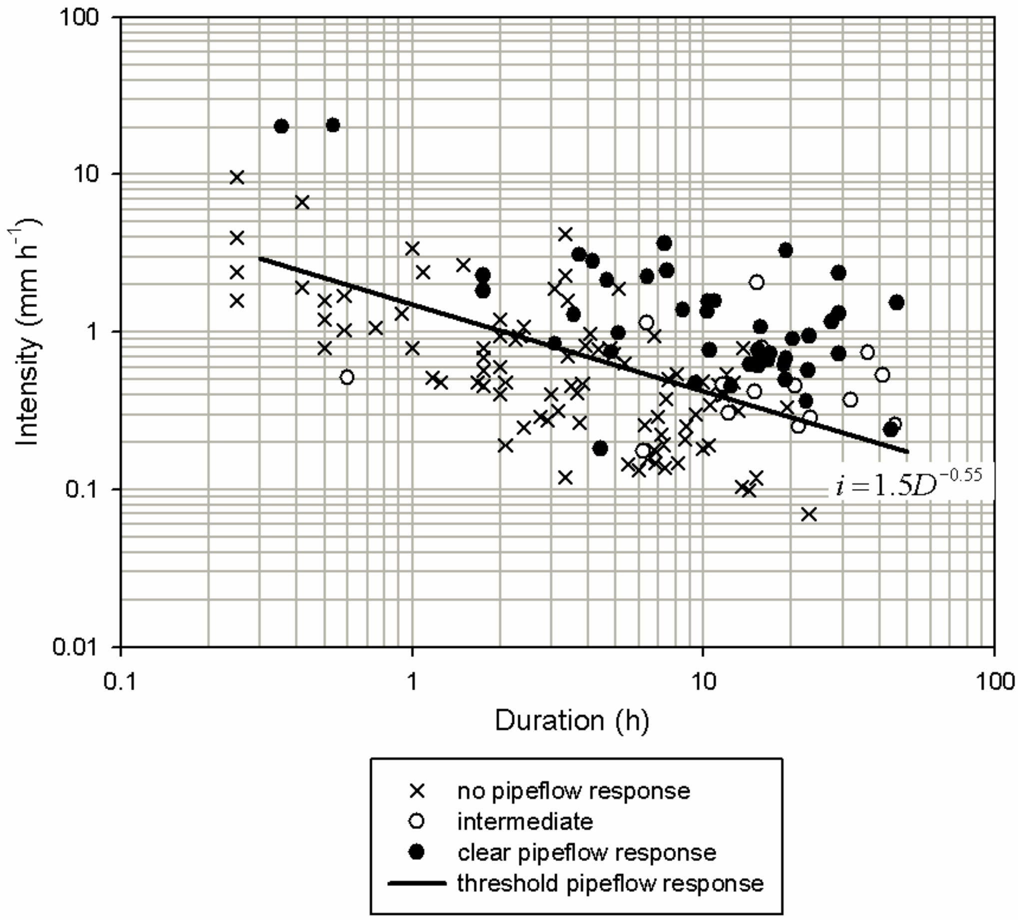


Fig. 8.6. Relation between duration (h) and intensity (mm) for 151 rainfall events at the study site, with indication of the threshold for pipeflow response.

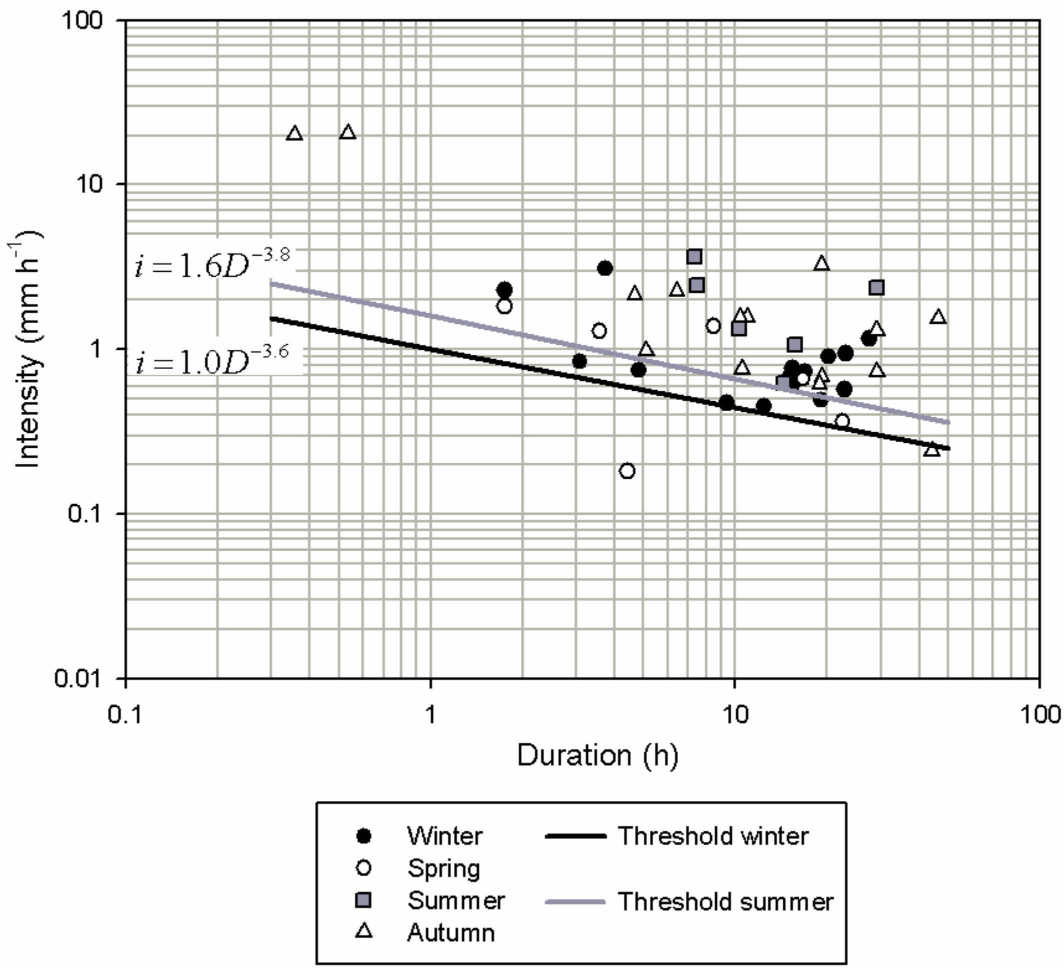


Fig. 8.7. Influence of seasons on the pipeflow response threshold.

The soil pipe bottom is located at ca. 120 cm depth at P2 and at ca. 80 cm depth at P5. At the most upslope piezometer (P1), the groundwater table is always within 90 cm below the soil surface. More downslope (P2 and P3), the groundwater table is deeper than the pipe except during extreme events. Downslope, the groundwater table at P4 stays below 100 cm the greatest part of the year, except in the winter months. Right next to the collapsed pipe (P5), water level measurements are within 80 cm for most of the year. This piezometer P5 is located within a meter of the pipeflow and probably does not show independent groundwater levels. Even in summer, pipeflow is observed although the groundwater table is below the depth of the pipe (except at P1 and P5).

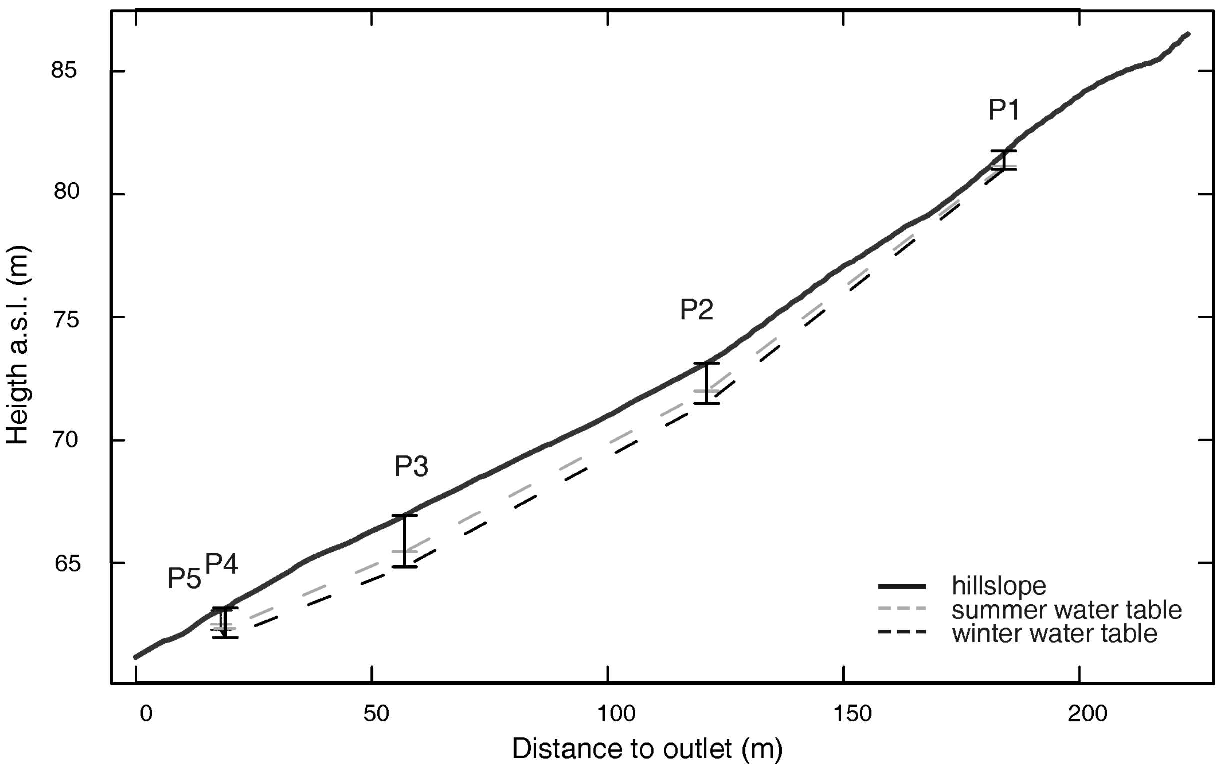


Fig. 8.8. Hydraulic gradient along the hillslope based on the summer and winter water table measurements in 5 piezometers (P1, P2, P3, P4 and P5).

Fig. 8.8 gives an indication of the hydraulic gradient between the piezometers for an average summer and winter condition, although the situation in between two piezometers is not exactly known. Especially upslope the profile, the hydraulic gradient is steeper than the slope gradient. Based on soil augerings in a dry period (July 210), the hydraulic gradient is steeper in the part directly downslope of P1, where the depth to the water table increased with 80cm on a distance of 20 m. This might point to tilted less-permeable layers, e.g. from landsliding activity in the past.

8.3.2. Chemical analysis of the different flow paths

Table 8.1 shows the characteristics of the five sampling moments. The pipeflow regime during the sampling period is further illustrated in Fig. 8.9. Mean ion concentrations, EC and pH of the five sampling moments and their significant differences according to a Tukey t test are shown in Table 8.2. The most important result is that the samples of the pipeflow differ significantly from those of rainfall for all ions except K^+. There are also some significant differences between pipeflow and groundwater samples, but the differences are smaller compared to rainfall. The concentrations of Ca^{2+}, Mg^{2+}, HCO_3^- and Cl^- of the pipeflow do not differ significantly from one or more groundwater samples. A similar trend can be observed for EC. Obviously, rainfall contains fewest ions and has the lowest EC values. Less difference is found in pH.

Table 8.1. Characteristics of the five sampling moments.

N°	Date	Preceding rainfall 2 days (mm)	Preceding rainfall 5 days (mm)	Pipe discharge ($l\ s^{-1}$)	Note
1	23/12/2010	0.6	0.6	0.305	snow
2	07/02/2011	0.0	1.4	0.250	
3	01/03/2011	1.8	11.6	0.435	
4	28/03/2011	0.0	0.4	0.220	
5	12/04/2011	0.8	0.8	0.167	

The chemical composition of the different water samples was compared using Piper diagrams. These diagrams confirm that water flowing through the soil pipes resembles mostly the groundwater samples (Fig. 8.10). In general, this trend is more pronounced for the cations than for the anions. The correspondence indicated by the Piper diagram only concerns the proportions of the different cations and anions, without information about the absolute concentrations.

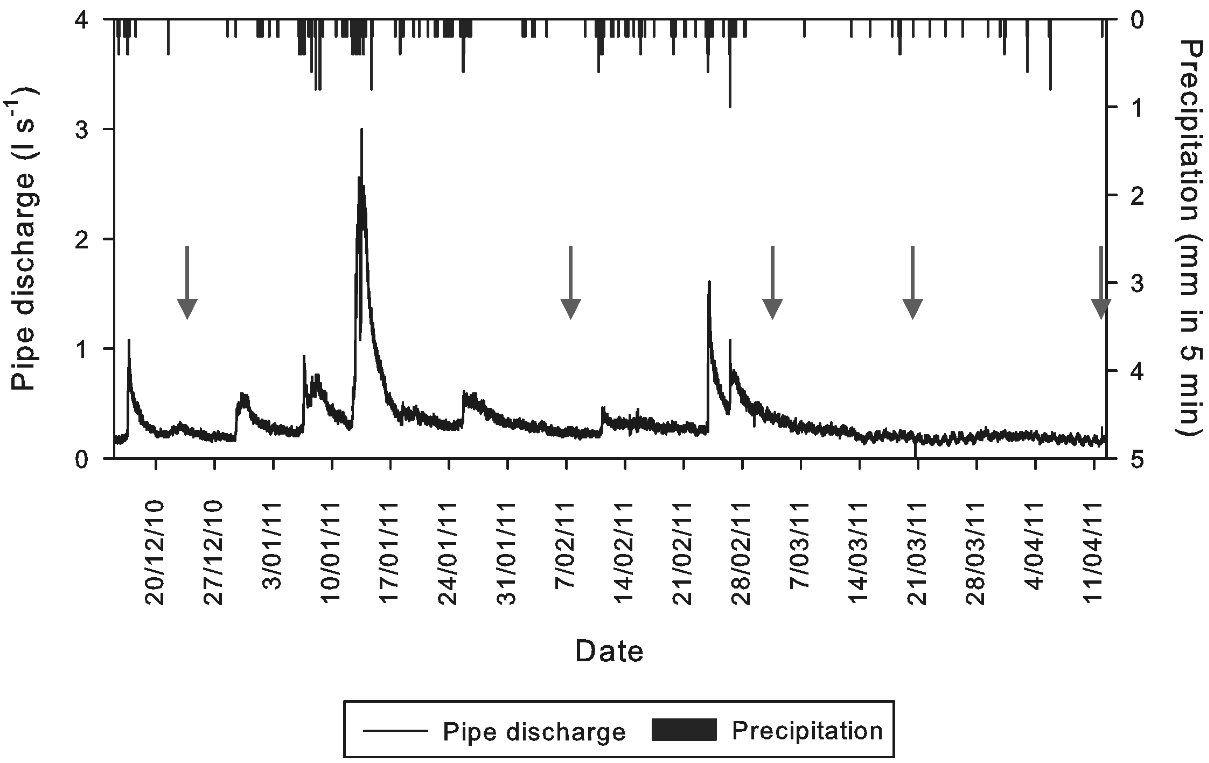


Fig. 8.9. Response of pipeflow to rainfall during the sampling period (December 2010 – April 2011). Arrows indicate the days when water samples were collected.

Table 8.2. Mean concentrations of the five samplings of the (a) cations (mg l^{-1}) and (b) anions (mg l^{-1}), electrical conductivity (EC, $\mu S\ cm^{-1}$), pH and total dissolved solids (TDS, mg l^{-1}).

(a)	Ca^{2+}		Mg^{2+}		Na^{+}		K^{+}		Si^{4+}	
P1	103.8	B	7.7	CD	12.7	C	1.0	C	7.3	B
P2	80.2	C	6.8	CD	16.6	B	1.0	C	9.9	A
P3	58.2	D	5.4	E	9.5	D	1.1	C	7.9	B
P4	33.6	E	2.8	F	5.5	E	1.3	C	6.1	C
P5	84.6	BC	8.1	BC	13.7	C	5.0	B	3.4	D
Pipe	98.2	BC	9.8	B	20.0	A	1.9	C	9.3	A
Rainfall	3.0	F	0.3	G	2.0	F	1.5	C	0.7	E
Stream	137.2	A	13.3	A	21.5	A	6.5	A	10.9	A

(b)	CO_3^{2-}/HCO_3^{-}		Cl^{-}		SO_4^{2-}		NO^{3-}		EC		pH		TDS	
P1	221.5	C	65.3	A	1.7	E	42.3	B	373.4	C	6.8	B	451.5	B
P2	172.5	D	42.3	B	14.2	C	41.5	B	302.2	C	6.8	B	354.8	C
P3	160.3	D	20.4	C	8.8	D	16.0	D	293.2	C	6.7	B	271.9	D
P4	114.5	E	6.4	CD	1.5	E	6.0	E	168.0	D	6.3	C	171.2	E
P5	291.3	B	14.1	CD	1.9	E	29.0	C	344.0	C	6.7	B	447.4	B
Pipe	174.3	D	65.4	A	30.6	B	63.0	A	551.2	B	7.0	B	438.8	B
Rainfall	5.3	F	2.2	D	3.2	E	3.7	E	33.7	E	6.8	B	15.5	F
Stream	351.0	A	63.9	A	37.9	A	49.5	B	836.7	A	7.6	A	643.2	A

P1-P5: piezometers, see Fig. 8.2 for location.
Within each column, means with a different letter differ significantly according to t-test (Tukey) at $p < 0.05$, in the order A>B>C>D>E>F.

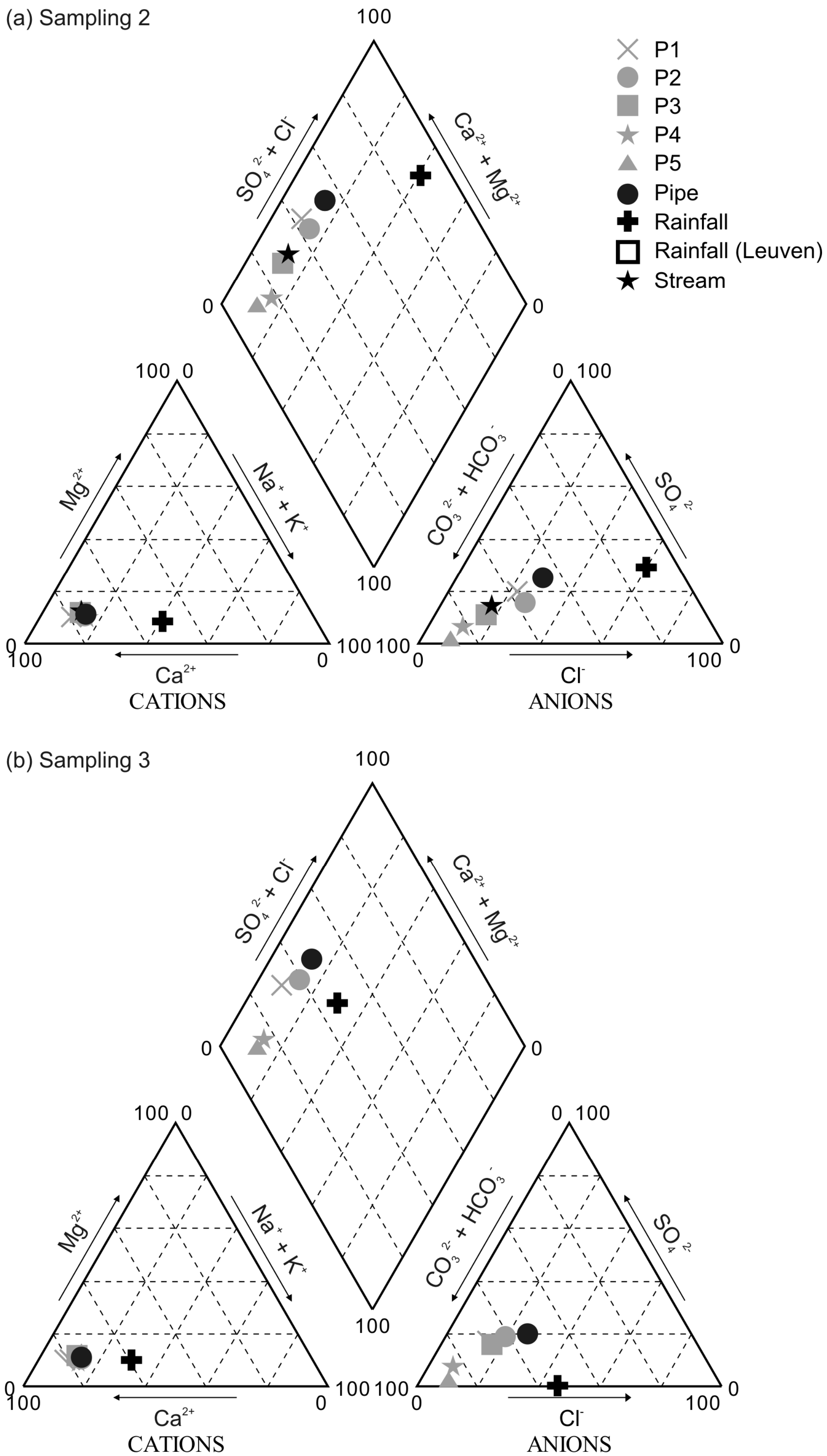
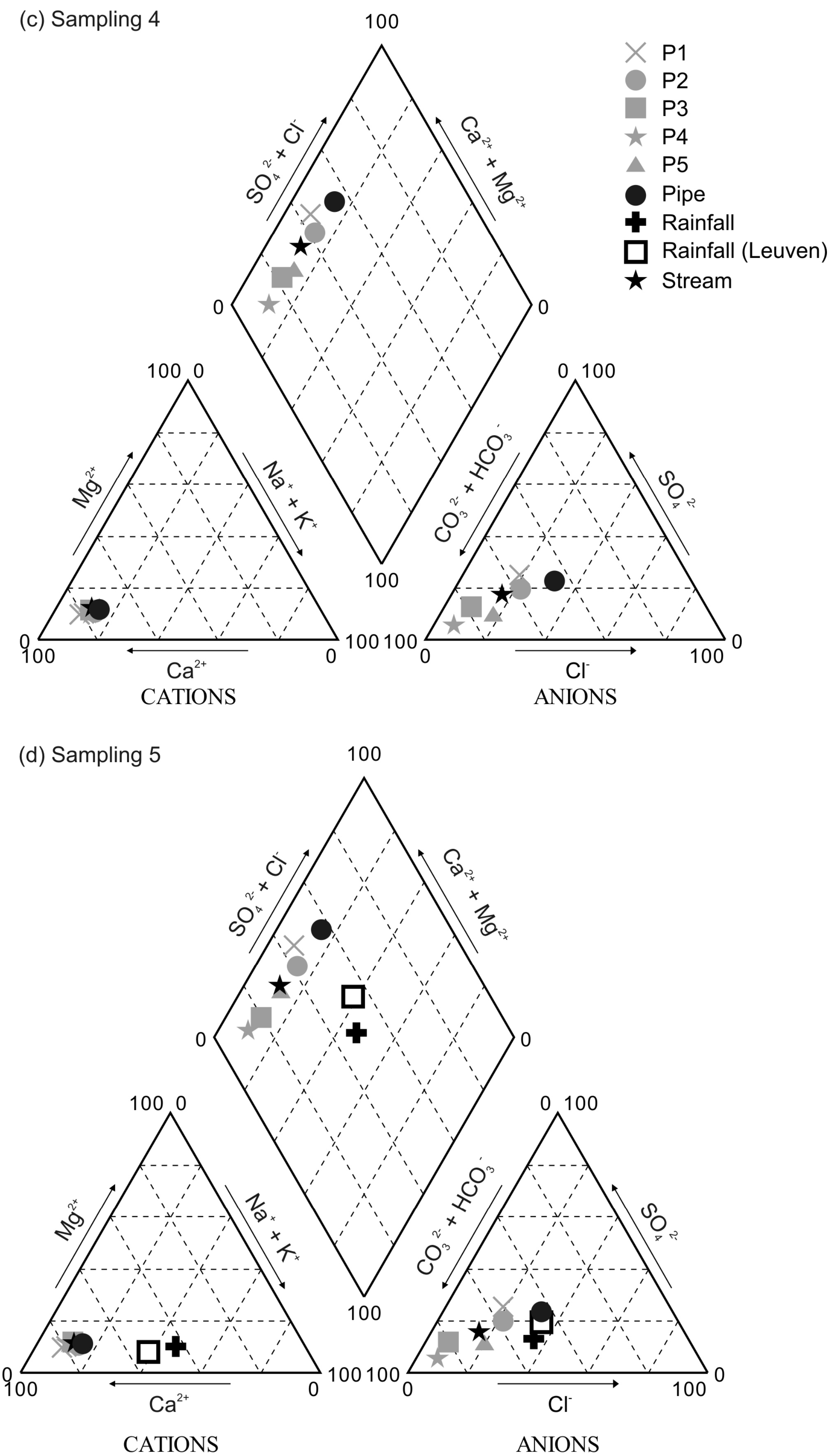


Fig. 8.10. Piper diagram for four sampling moments: (a) 07/02/11, (b) 01/03/11, (c) 28/03/11 and (d) 12/04/11.



Continued Fig. 8.10. Piper diagram for four sampling moments: (a) 07/02/11, (b) 01/03/11, (c) 28/03/11 and (d) 12/04/11.

8.4. DISCUSSION

Through continuous monitoring and chemical water analysis, information about the hydrological functioning of soil pipes is obtained. However, the relatively short monitoring period and the fact that this study focuses on one study site limit the interpretation of the results. It is therefore clear that this study should be seen as a starting point for further research exploring pipeflow dynamics in greater detail. The first results are discussed below.

8.4.1. Response of pipeflow to rainfall events and groundwater fluctuations

The presence or absence of pipeflow response was not related to the antecedent rainfall of the 2 or 5 preceding days, but it can be assumed that the antecedent soil moisture content played a role. In summer, when the soil was dry, less storms were able to increase the pipeflow discharge significantly (Fig. 8.7). Unfortunately, no data of soil moisture content were available, but the groundwater table could be an indication of the pre-event wetness of the soil. It can be assumed that infiltrating rain water will only contribute significantly to (subsurface) runoff after a critical groundwater level is reached (McCaig, 1983). Similar to the observations of Richard and Cowland (1986), the responses of individual piezometers were inconsistent from one storm to another, illustrating localized and changeable flow patterns determined by the subsurface flow system (Hencher, 2010).

Even in summer, pipeflow is observed although the groundwater table is below the depth of the pipe (except at P1 and P5). The groundwater at P1 is at shallow depth (< 90 cm below the soil surface) all seasons and sometimes exfiltrates (spring). The similar chemical composition and response of P1 and the pipeflow suggest that groundwater at P1 is in connection with the water in the soil pipes. It is however not clear how it finds its way to the pipes more downslope, visible from the most upslope collapse near P3. Augerings in between revealed no shallow water table between P1 and P3 (July 2010). Landsliding probably caused the pushing up of a clay layer, resulting in the shallow water table at P1, while this homogeneous clay substrate was not found within several meters below the surface more downslope. The observations of mottling and groundwatergley from the augering and profile pit close to P4 and P5, described in Chapter 7, also mainly correspond to the fluctuations in P4. During the augering, mottling was observed from 50 cm below the surface but this is higher than the level of P4 in winter (except short peaks). In P5, the water table was on average at 40 cm during the winter months. This can explain the shallow mottling signs although they can be from a former period with more shallow water tables as well.

8.4.2. Origin of the water flowing through the pipe

Despite the fast response of pipeflow to rainfall, the chemical water analysis suggests that mainly soil water with a longer residence time in the soil feeds the pipeflow. For example, the pipeflow discharge at sampling 3 was 66% higher than the one at sampling 5 (considered as baseflow). If we assume that the increase in discharge was due to new rainfall water entering the pipe, this should result in a corresponding dilution and a decrease of the total dissolved solids. Instead, the composition of pipeflow at sampling 3 could be considered to be 91% old (pre-event) water and only 9% new water (based on an average 15.5 mg l^{-1} of TDS in rainfall). It can therefore be concluded that pipeflow predominantly consists of old water, displaced by matrix flow (i.e. not by macropore flow) also defined as a type of piston flow (Jones, 2004a; Jones, 2010). Similarly, water quality and hydrograph analysis indicate a dominance of old water in peatland in the UK (Neal and Rosier, 1990; Chapman et al., 1993; Sklash et al., 1996). Sklash et al. (1996) reported that direct rainfall inputs only contributed minimally to pipeflow but rainfall affected the water table elevations, supporting the importance of a rising phreatic surface suggested by previous studies (e.g. Jones, 1982; McDonnell, 1990).

However, new water played an important role in the runoff generation of pipeflow in the Amazonian rainforest in Peru (Elsenbeer et al., 1995; Elsenbeer and Lack, 1996) and Ouachita Mountains in the USA (Turton et al., 1995). Direct rainfall contributions can also result from saturation excess overland flow infiltrating in collapsed pipes (Sklash et al., 1996; Jones, 2010). Consequently, the pipe can be fed directly from precipitation via by-pass flow through macropores (e.g. earthworm burrows, Chapter 7) and soil cracks, but also indirectly from saturated parts of the soil. In New Zealand, McDonnell (1990) also concluded that precipitation, rapidly infiltrating via vertical macropores, mixed with soil water and groundwater with a longer residence time and

then flowed downwards through well-connected macropores (Sklash et al., 1996). The same probably applies for our study site.
It should be commented that only a limited number of samplings was done in this study, and all of them at the end of winter and beginning of spring. The water table is at the most shallow position of the year in this period, which increases the possibility that pipeflow is fed by rising groundwater. More water samples during all seasons should be analysed to determine if the above described piston flow is less observed when groundwater tables are deeper. In general, pipeflow will be a variable mix between old and new water, with fractions that vary between environments, events and through one storm as well (Jones, 2010). First, rapid drainage of short residence water through the pipe was indicated by the similarity of response and sodium concentrations measured in rainfall and pipeflow (Hyett, 1990 in Jones, 2010; Jones, 2004a). Later in the storm, older groundwater diluted the rainfall signal (Jones, 2004a). Contrastingly, Jones (2010) concluded that generally more old water is observed during light storms and at early stages of the storm, while the reversed balance occurs in the latter stages of a storm and with longer and heavier events.

On the other hand, Jones and Connelly (2002) observed that pipes can feed groundwater as well. In our case study, it is clear that the pipe and the groundwater at P5 are connected. However, one could question if the similarity between P5 and pipeflow is due to 'pipe leakage' or due to groundwater flowing into the pipe. Also exchange between surface and subsurface routes has been reported in the humid tropics (Elsenbeer and Vertessy, 2000; Chappell and Sherlock, 2005; Jones, 2010). Resurgence of pipeflow generating overland flow was observed at the study site as well, where the pipe got blocked during a heavy event. This water entered the pipe again at the next downslope collapsed pipe.

8.5. CONCLUSIONS

This chapter aims to provide a first insight in the dominant water source of soil pipes and their hydrological functioning. Although the sampling period is relatively short (i.e. 4 months), the hydrochemical analysis consistently showed a significant dissimilarity between the composition of rainwater and pipeflow water. The composition of the pipeflow was most similar to the samples of groundwater. This similarity was also supported by the results of the EC and the total dissolved solids. The fast response of pipeflow and groundwater table on rainfall events however indicates that the influence of rainfall can not be neglected either. Pipeflow is also observed when the groundwater table is deeper than the pipe depth. It can therefore be hypothesized that rainfall (new water) pushes pre-event water (old water) from the soil into the pipe by a type of piston flow, explaining the similar chemical composition of groundwater and pipeflow. Further investigation of more samples taken over a longer period with different rainfall regimes is however necessary to identify the relationship between rainfall, groundwater and pipeflow, including seasonal variations, and to allow for modelling. Furthermore, the results indicate that monitoring the water level upslope of the CP is important to gather insight into the hydrological functioning of piping.

Chapter 9

Conclusions and scope for further research

Of all erosion processes, piping erosion is the most difficult to study as it occurs below the soil surface and as we only witness its presence at an advanced stage of development, i.e. when the pipe roof collapses. Nevertheless, the research presented in the previous chapters allows us to answer the research questions following from the objectives formulated in the introduction and to formulate suggestions for further research.

9.1. HOW EFFECTIVE ARE THE EVALUATED TECHNIQUES FOR DETECTING PIPES AND SUSCEPTIBILITY TO PIPING?

Geophysical detection methods turned out not to be successful (yet) in detecting subsurface pipes in loess-derived soils (Chapter 2), because the pipes are too small to be detected in soil material with such high silt contents with the standard methods. However, the potential of these methods has been reported in other environments such as peat (Holden et al., 2002). The fact that piping erosion is not easily detected at the surface undoubtedly hampers piping research, which therefore stays mainly restricted to CP, as in this dissertation. One third of all parcels with CP found during the field survey were observed by analyzing aerial photographs. Although analysis of orthophotos can help to detect CP, detailed field surveys remain necessary. Additionally, Chapter 2 demonstrates that the susceptibility to piping erosion of contrasting loess-derived soil horizons can be evaluated in a quantitative way using the pinhole test (Sherard et al., 1976a) with an adapted procedure for natural soils. The decalcified and calcareous loess horizon (C_1 and C_2 respectively) showed a significantly higher sediment response than upper horizons (A_p and B_t).

9.2. WHAT IS THE SIGNIFICANCE OF PIPING IN THE FLEMISH ARDENNES?

This study resulted in a regional inventory of collapsed pipes (CP), unique for the European loess belt. From the field survey in a 236 km² representative study area, it becomes clear that the loess-derived soils in the Flemish Ardennes in Belgium are susceptible to piping erosion, causing collapse of the topsoil and formation of discontinuous gullies. The 300 mapped sinkholes and 195 mapped closed depressions have an average depth of 0.6 m and 0.3 m respectively and an average diameter of 1.1 m and 1.3 m respectively, but there is a large variation in the data. Furthermore, subsurface erosion causes significant soil losses (2.4 – 4.6 t ha^{-1} yr^{-1}) for a land use –pasture– that is typically considered to be non-susceptible to surface erosion (Chapter 3).

In general, piping will lead to an increased hydrological and sediment conductivity of the catchment. It is remarkable that the sediment export by the rivers of the Flemish Ardennes (1.5 – 2.5 t $ha^{-1}yr^{-1}$) is 7-fold those of the rivers in the Demer catchment (0.02 – 0.04 t $ha^{-1}yr^{-1}$, VMM, 2007). The difference is mainly attributed to the higher drainage density (1.46 km km^{-2}) and the steeper slope gradient (VMM, 2007). Within the framework of this research, it was investigated if the subsurface erosion could have contributed to these high sediment yields as well. Although the local subsurface soil loss of the pastures with CP can be up to half the sediment export by the rivers (0.6 – 1.2 t ha^{-1} yr^{-1}), the contribution of subsurface soil loss at the scale of a catchment with 20% pastures having slope gradients > 4% is rather small (0.5% or 0.006 – 0.012 t ha^{-1} yr^{-1}). A geomorphological implication of piping is that the pipes and pipe collapses, developing mainly in concave thalwegs in the study area, generally contribute to thalweg incision. The thalwegs become deeper, which may in turn lead to the intensification of other processes (drainage, subsurface flow) on the slopes. As pipes mainly occur in piping-sensitive (loess-derived) soils, the geomorphological effect of piping will only be present within the loess layer and will not lead to incision into Tertiary substrate. From the hydrological monitoring (Chapter 8), it followed that pipes can quickly transmit runoff/water downslope. In the study area, ca. 3% of the thalwegs in pastures were affected with CP. Therefore, the hydrological significance of piping on the regional scale is limited, at least when only considering the pipes that are visible through collapses.

9.3. WHICH FACTORS CONTROL THE SPATIAL PATTERNS OF COLLAPSED PIPES IN THE STUDY AREA? CAN A SUSCEPTIBILITY MAP FOR PIPE COLLAPSE BE CREATED?

Different topographical and environmental factors controlling the development of pipe networks and adjacent pipe collapse are reported for regions with different characteristics, all over the world. Our results confirm that in loess-derived soils in temperate regions, a wide range of slopes (i.e. 8–24%) may be affected by piping erosion. Furthermore, the probability of piping increases on hillslopes with a concave profile and plan curvature, enhancing subsurface flow concentration (Fig. 4.3). The necessary subsurface water supply is also supported by a characteristic lithology for the study area, consisting of an alternation of sands and less-permeable smectite-rich clays and giving rise to numerous springs. The zones with soil profiles on shallow loess over a relatively thin layer of homogeneous blue massive clays (Aalbeke Member) are most prone to piping. Almost all CP were observed under pasture, but land use is not independent of topography and drainage conditions. In the Flemish Ardennes, pastures dominate the hillslopes that are less suitable for cropland because of their steepness and wetness, sometimes in combination with a shallow loess cover (also forest on these hillslopes). In the study area, more pastures (25%) are located on the clay-rich Aalbeke Member than the overall occurrence of this lithological layer (8% of the study area). In Chapter 6, the spatial patterns of CP were compared to those of landslides (LS) in the study area, both mapped and predicted. At least 24.5 % of the sites with CP were related to the occurrence of an observed landslide (Table 6.2) and 75% of the pastures with CP contained mimimum one pixel with a high LS susceptibility. Although poorly drained LS can change the hillslope hydrology and enhance piping, it is clear that other causes (e.g. broken field drains) may result in concentrated subsurface flow as well.

Two methods for predicting piping susceptibility were evaluated in Chapter 5. When modelling susceptibility to pipe collapse, selecting suitable sites without piping for the model is complex. In the present study, locations of parcels without CP that were similar to locations of CP in parcels with piping were selected to allow for correct comparison. The output of the logistic regression model represents the most important factors controlling piping occurrence, i.e. topographical threshold (slope, drainage area) in combination with a sufficient water supply (Table 5.1).

Topographical water convergence zones (short distance-to-thalweg, concave curvature) and zones with a larger probability of having shallow water tables (clay-rich lithology, wet soil drainage class) are further indications for locations susceptible to pipe collapse.

More than the exact slope gradient, the relationship of the slope gradient (S) with the contributing drainage area (A) is important for explaining the occurrence of CP. The derived topographical thresholds, used for a second susceptibility map, provide a good picture of piping susceptibility in the region (Fig. 5.8). The observation that the SA model performs equally well as the logistic regression model only holds for this study area because of the particular relation between topography and lithology. Both susceptibility maps are useful tools for local land management, allowing one to avoid changes in hydrological situation or land use that stimulate piping at locations with a high susceptibility to piping even if no observations of pipe collapse have been made.

9.4. WHICH LOCAL CAUSAL FACTORS DETERMINE PIPE DEVELOPMENT? A FOCUS ON SOIL CHARACTERISTICS AND HYDROLOGICAL FUNCTIONING

In Chapter 7, the role of soil characteristics and land use in the development of piping in the loess belt of Belgium was investigated. First, the hypothesis was tested that discontinuities in the soil profile favour piping erosion. We focused on discontinuities from soil characteristics that could vary with soil depth such as soil texture, saturated hydraulic conductivity, penetration resistance and bulk density. These characteristics as well as the biological activity in the soil were studied in detail for 12 representative soil profiles for different land use types. Twelve sites were selected in the Flemish Ardennes (Belgium): 4 pastures with CP, 4 pastures without CP, 2 sites under arable land without CP and 2 sites under forest without CP. Second, this study aimed at evaluating the interaction of the groundwater table positions (through soil augerings) and CP at more sites, with a focus on pastures, the land use where almost all CP in the study area are observed. Therefore, the position of the groundwater table was compared for 15 pastures with and 14 pastures without CP having comparable topographical characteristics (slope gradient and contributing area). Finally, the effect of the land use history on pipe collapse occurrence was evaluated for a database of 84 parcels with CP and 84 parcels without CP, currently under pasture. As to the first hypothesis, no clear discontinuities for abiotic soil characteristics in the soil profiles were observed at the depth where pipes occur, but pastures with CP had significantly more earthworm channels and mole burrows at larger depths (at > 120 cm depth: > 200 earthworm channels per m^2 on average) than pastures without CP, arable land or forest (at > 120 cm depth: few or no earthworm channels left). The land use history did not appear to be different for the pastures with and without CP. Combining all results from soil profiles and soil augerings indicates that intense biological activity (especially by earthworms and moles), in combination with a sufficiently high groundwater table, favours the development of soil pipes in the study area (Fig. 7.13).

We therefore agree with Jones (1982) that pipeflow is generated by a combination of vertical infiltration through macropores and rising phreatic water tables. Jones (1982) reported these rising water tables to occur in areas away from the pipes, creating a hydraulic gradient in the direction of the pipes and hence drainage into the pipes. Similarly, we observed a high water table at a distance upslope of the pipes (P1, see Fig. 8.1 in Chapter 8) in connection with the pipes, when monitoring one field with pipes in detail. At this location, a shallow clay-rich layer was observed that was not detected at the location of the CP within 3 m. Furthermore, the chemical composition of the groundwater samples at P1 was similar to that of the pipeflow, suggesting that they are connected (Chapter 8). It was one of the main objectives of Chapter 8 to investigate the relation between pipeflow, rainfall and groundwater, and to determine the dominant source of the water flowing through the soil pipes through a hydrochemical and a hydrometric analysis. At five moments in the period December 2010 – April 2011, we sampled rainfall, groundwater (at five locations), the downslope stream and the pipeflow. The hydrochemical analysis included the measurement of the main ions (Mg^{2+}, Ca^{2+}, K^+, Na^+, Si^{4+}, Cl^-, SO_4^-, NO_3^-), the pH and the electrical conductivity. The hydrometric analysis described the response of the pipeflow and the water table on rainfall events, monitored for the period February 2010 – April 2011. Despite the fast responses of pipe discharge on rainfall events (Fig. 8.8), the chemical composition of the pipeflow was most similar to the groundwater samples and clearly different from rainwater. Therefore, it is hypothesized that rainfall pushed pre-event water from the soil into the pipes by a type of piston flow (matrix flow).

9.5. WHICH CONDITIONS NEED TO BE MET TO INDUCE PIPING IN THE FLEMISH ARDENNES?

Here we summarize all elements that influence piping erosion in the Flemish Ardennes, collected throughout the research (Fig. 9.1). A certain slope gradient in combination with a sufficient contributing area is needed, although the hydraulic gradient is more important than the surface slope gradient. Furthermore, the combination of loess-derived soils underlain by less-permeable clayey substrates favours the occurrence of high/perched water tables and springs. Other factors creating a concentrated water flow such as landsliding (see Chapter 6), drainage from roads or blocked/broken field drains may add to a favourable hydrological situation for piping as well. In addition, many of the fields that match a steep topography and poor drainage are under pasture. This land use is the most favourable for biological activity by earthworms and small mammals. Anecic earthworm species enhance rapid vertical infiltration and mole burrows favour lateral flow in the soil profile. Preferential flow paths are generated and, with the necessary water supply and subsurface flow, can develop into pipes.

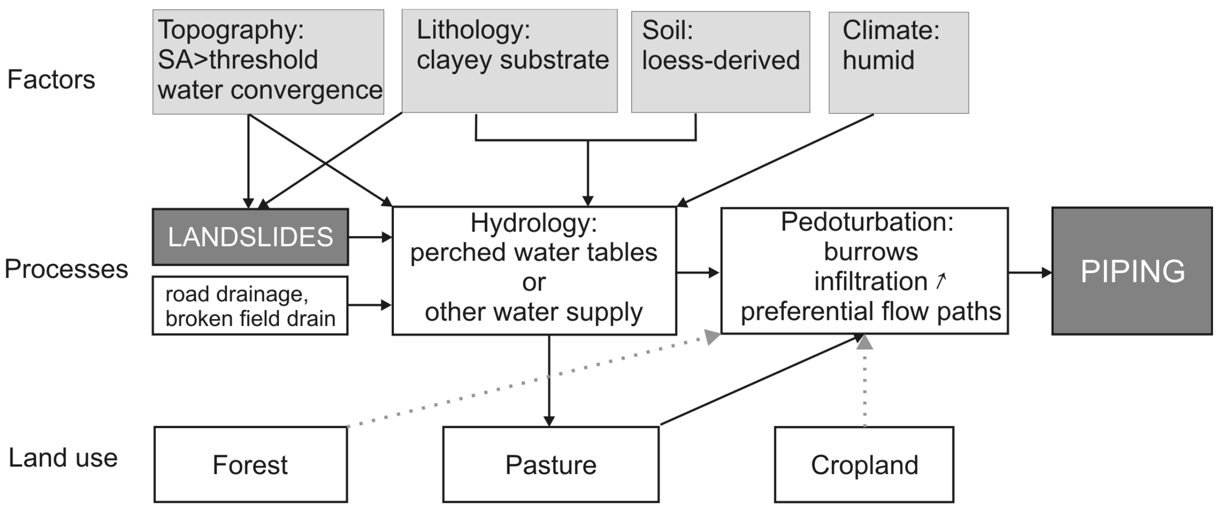


Fig. 9.1. Interactions between processes and factors controlling piping erosion in the Flemish Ardennes. The factor land use is considered separately in this diagram. Black arrows indicate a positive relation, grey dotted arrows a negative.

Can we use the structural model shown in Fig. 9.1 to understand why piping is present or absent in other regions with loess derived soils?

In the Bonn area in Germany, for example, where piping was studied in loess-derived soils in a temperate humid climate as well (annual P = 670 mm, PET = 616 mm; NewLocClim, FAO, 2005), similar factors are reported. First, the CP were mainly observed in pastures on hillslopes with a sufficient slope gradient (e.g. 11 – 44 %), generally slightly steeper than in the Flemish Ardennes. Second, Botschek et al. (2002a) pointed to the role of biological activity in pipe initiation as well. Furthermore, the soils developed in non-calcareous loess covering clay-rich deposits from the Devonian basement mixed with rock fragments (Botschek et al., 2002a).
A 192 km^2 hilly area with loess-derived soils in central Belgium, southwest of Leuven (annual P = 747 mm, PET = 580 mm; KMI, 2011; NewLocClim, FAO, 2005), was considered as well. Most of the locations in this area plot more left on the SA graph (Fig. 9.2) than in the Flemish Ardennes, i.e. they have smaller contributing areas. There also are data in the area southwest of Leuven plotted above threshold 1 and 2, hence, susceptible to piping according to their topography. However, collapsed pipes were not observed in this area. This is probably due the fact that the loess cover south of Leuven does not rest on an impermeable substrate and therefore, lacks the occurrence of perched water tables, springs or landslides.
In the Moldavian plateau in Romania, gullying and landsliding occur frequently (Ionita, 2006). There are loess-derived soils under pasture and the contact of colluvium with B_t horizon creates a discontinuity in permeability. However, no piping is observed here (I. Ionita, 2011, personal communication). Most probably, the hydrological requirement is not fulfilled: annual precipitation is ca. 546 mm and the potential evapotranspiration is ca. 896 (NewLocClim, FAO, 2005), so no shallow water tables are observed. It should be mentioned that pipes are observed in other regions of Romania (e.g. Balteanu, 1986).

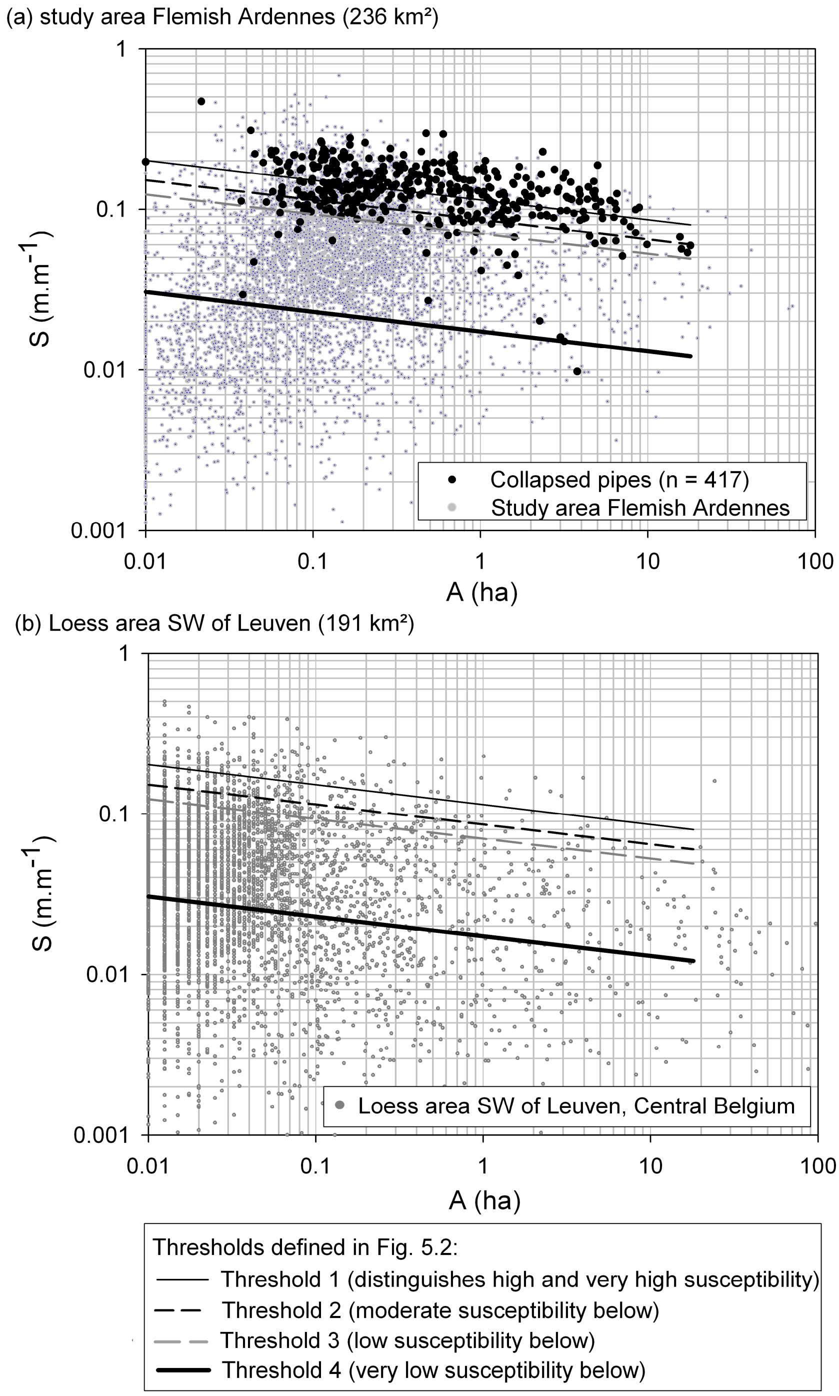


Fig. 9.2. Relation between slope gradient (S) and drainage area (A) of the Flemish Ardennes compared to the loess area south-west of Leuven.

9.6. WHAT ARE POSSIBLE PREVENTION AND REMEDIATION STRATEGIES FOR PIPE COLLAPSE?

Information about prevention and remediation strategies is scarce. Although not the main objective of this dissertation, the study revealed a number of observations concerning preventing and remediating piping and pipe collapses. From field observations and interviews, it became clear that the common methods of filling the CP with soil or construction material did not stop the problem. In most cases, new collapses appeared close to the previous ones, indicating that new flow paths were created. The following alternative remediation strategies were reported by farmers and land owners in the Flemish Ardennes as well:

(i) Artificial drainage pipes. However, when field drains get blocked or broken, they provide a concentrated subsurface water flow which can be the cause of piping instead.

(ii) An open ditch at the location of the pipe. This strategy is sometimes used when the pipes are clearly grouped in one flow line and at the border of a pasture, but it is not a realistic strategy in the case of irregular subsurface flow paths crossing the field.

(iii) Vegetation. Trees were planted at the spring upslope of the pipes in order to lower the water table and to reduce the amount of water flowing downslope to the pipes. However, the water uptake of the trees is limited in winter. In one case, a row of torn-bushes was planted above the pipe and CP to prevent cattle from getting injured by falling into CP. Although the piping process was not stopped, at least one of the farmers' main concerns was solved.

Several revegetation strategies have been proposed in literature as well from deep rooting grasses to poplar and willow poles following the lines of the pipes (e.g. Floyd, 1974; Hardie et al., 2007; Reports of governments of Tasmania and New Zealand). Vacher et al. (2004a) stated that the establishment of vegetation is highly desirable to increase evapotranspiration and reduce deep drainage. Floyd (1974) recommended a dense pasture to promote regular infiltration and to minimise soil cracking. In the Flemish Ardennes, however, CP were mostly observed in pastures, so this strategy can not be used in this area. Conversion to cropland after filling the collapses would probably reduce pipe development, but the soil loss due to surface erosion will be even worse (cfr. section 3.4.1). Other reported methods involve the destruction of existing pipes and measures to divert water away from pipe-prone areas (e.g. Colcough, 1973; Floyd, 1974; Boucher, 1995). Prolonged ponding should be avoided (Vacher et al., 2004a). Also in the Flemish Ardennes, it is recommended to maintain a good drainage, for example by keeping ditches open, in order to prevent concentration of water.

9.7. SCOPE FOR FURTHER RESEARCH

The present thesis was the first regional study on CP in the loess belt of Europe. Most of the research questions formulated in Chapter 1 were answered in this dissertation. Some answers, however, especially concerning the non-destructive detection and hydrological aspects of piping, are not complete at present. Also additional research questions have arisen as there are still gaps in our knowledge about piping erosion. Therefore, suggestions for further research are formulated in the next paragraphs.

- Standard measurement and interpretation strategies of geophysical detection methods (ERT, GPR and EMI) were not successful in detecting soil pipes (Chapter 2), although their use in other environments showed their potential. The tests were only carried out at one study site, but could be extended to more sites with different texture and pipe morphology, possibly even under controlled lab conditions. Refining and adapting the method and interpretation, as well as computer simulations testing the possibilities of detecting pipes deserve further investigation. For example, it would be interesting to evaluate the use of a tracer solution such as sodium chloride, which was successfully used by (Holden, 2004) to determine the hydrological connectivity of soil pipes with GPR in peat in the UK.

- Although a first attempt was made to investigate the hydrological functioning of the pipes, the collected dataset was rather limited and served more as a proof of concept that should be further developed. The collected data on rainfall, pipeflow discharge and groundwater, preferentially during a longer monitoring period, could be used to gain more insight into the temporal dynamics of piping erosion. Although hydrological modelling of the process was not possible within the timeframe of this research, some possibilities were explored during a short study stay at the Imperial College London in collaboration with Dr. W. Buytaert. The hydrological model TOPMODEL or an adapted version should be evaluated for modelling catchments with pipeflow. If it is possible to predict the dynamics of the piping process, different scenarios can be tested, e.g. the effect of different land use or climate change resulting in higher precipitation during the winter. Furthermore, a catchment with a high susceptibility to pipe collapse (susceptibility map Chapter 5) and monitored runoff discharge (data Flemish Government, VMM) could be studied. Hence, it could be tested whether a model incorporating pipeflow enhances the prediction of the runoff.

- Chapter 5 showed the potential of logistic regression and/or topographical thresholds methods, for the development of a susceptibility map of the study area. As the occurrence of pipe collapses is not restricted to these five municipalities, the map could be extended. It is recommended to use the above mentioned methods in order to create a susceptibility map for the complete Flemish Ardennes, if possible including Pays de Collines.

- As the present reclamation measures seemed not completely adequate to control piping in our study area, further research on remediation strategies is necessary.

- Apart from the recommendations for future research in the study area, we would learn more about piping erosion by extrapolating the prediction techniques and comparing the results to similar regions with and without piping erosion. The use of logistic regression and topographical thresholds for the creation of susceptibility maps for pipe collapse (Chapter 5) should be tested in other regions, e.g. the area around Bonn (Germany), as well.

Abrahams, A.D., 1980. Channel Link Density and Ground Slope. Annals of the Association of American Geographers 70, 80-93.

Acciardi, R.G., 1982. Quantification of Pinhole Test Equipment Hydraulic Characteristics. Available from Engineering and Research Center, Denver CO. Report No. REC-ERC-82-15, September 1982.

AGIV, 2001a. Tertiary geological map of Belgium. Digital file.

AGIV, 2001b. Soil map of Belgium. Digital file.

AGIV, 2004. Landbouwgebruikspercelen, toestand 01/01/2004, Vlaamse Landmaatschappij - afdeling Mestbank. Digital file.

AGIV, 2006. Orthophoto colour 1: 12 000, GIS Oost-Vlaanderen, Provincie Oost-Vlaanderen, AGIV.

Ahmed, S., Carpenter, P.J., 2003. Geophysical response of filled sinkholes, soil pipes and associated bedrock fractures in thinly mantled karst, east-central Illinois. Environmental Geology 44, 705-716.

Allison, P.D., 2001. Logistic Regression Using the SAS System: Theory and Application. Wiley Interscience, New York.

Allred, B.J., Fausey, N.R., Peters, L., Chen, C., Daniels, J.J., Youn, H., 2004. Detection of buried agricultural drainage pipe with geophysical methods. Applied Engineering in Agriculture, ASAE 20, 307-318.

Arulanandan, K., Heinzen, R.T., 1977. Factors influencing dispersive clays and methods of identification. In: Sherard, J.L., Deckers, R.S. (Eds.), Dispersive clays, related piping and erosion in geotechnical projects. ASTM Special Technical Publications 623, pp. 202-217.

Attou, F., Bruand, A., Le Bissonais, Y., 1998. Effect of clay content and silt-clay fabric on stability of artificial aggregates. European Journal of Soil Science 49, 569-577.

Baillie, I.C., 1975. Piping as an erosion process in the uplands of Sarawak. J. Trop. Geography 40, 9-15.

Baillie, I.C., Faulkner, P.H., Espin, G.D., Levett, M.J., Nicholson, B., 1986. Problems of Protection Against Piping and Surface Erosion in Central Tunisia. Environmental Conservation 13, 27-32.

Balteanu, D., 1986. The importance of mass movement in the Romanian sub-Carpathians. Zeitschrift für Geomorphologie Supp 58, 173-190.

Barahona, E., Quirantes, J., Guardiola, J.L., Iriarte, A., 1990. Factors affecting the susceptibility of soils to interrill erosion in South-eastern Spain. In: Rubio, J.L., Rickson, R.J. (Eds.), Strategies to combat desertification in Mediterranean Europe. Commission of the European Communities, EUR 11175, pp. 216-227.

Barendregt, R.W., Ongley, E.D., 1977. Piping in milk River Canyon, south eastern Alberta - a contemporary dryland geomorphic process. In: Erosion and soil material transport in Inland waters. pp. 233-243.

Batelaan, O., Meyus, Y., De Smedt, F., 2007. De grondwatervoeding van Vlaanderen. (Groundwater recharge in Flanders) Tijdschrift Water 28, 64-71.

Batog, A., Hawrysz, M., Strózyk, J., 2007. Estimation of susceptibility to colloidal erosion of cohesive soils using the pinhole test. Geologos 11, 421-427.

Beckedahl, H.R., 1998. Subsurface soil erosion phenomena in South Africa. In: Petermanns Geographische Mitteilungen Justus Perthes Verlag Gotha, Ergaenzungsheft 290, pp. 128.

Bell, D.H., Glassey, R.J., Yetton, M.D., 1986. Chemical stabilisation of dispersive loessical soils, Banks Peninsula, Canterbury, New Zealand. In: Proceedings 5th International Congress, International Association of Engineering Geology. AA Balkema, pp. 2193-2208.

Bell, F.G., Walker, D.J.H., 2000. A further examination of the nature of dispersive soils in Natal, South Africa. Quarterly Journal of Engineering Geology and Hydrogeology 33, 187-199.

Benito, G., Gutierrez, M., Sancho, C., 1993. The Influence of Physicochemical Properties on Erosion Processes in Badland Areas, Ebro Basin, Ne-Spain. Zeitschrift fur Geomorphologie 37, 199-214.

Blocken, B., Poesen, J., Carmeliet, J., 2006. Impact of wind on the spatial distribution of rain over micro-scale topography: numerical modelling and experimental verification. Hydrol. Process. 20, 345-368.

Boardman, J., Poesen, J., 2006. Soil erosion in Europe. Wiley (J.), Chichester.

Bocco, G., 1991. Gully Erosion - Processes and Models. Progress in Physical Geography 15, 392-406.

Bollinne, A., 1982. Etude et prévision de l'érosion des sols limoneux cultivés en Moyenne Belgique. Thèses de doctorat, Université de Liège.

Bond, R.M., 1941. Rodentless rodent erosion. Soil Conservation (6) 10, 269.

Borselli, L., Torri, D., Poesen, J., Salvador-Sanchís, P., 2001. Effects of water quality on infiltration, runoff and interrill erosion processes during simulated rainfall. Earth Surface Processes and Landforms 26, 329-342.

Botschek, J., 2002. Spezielle Prozesse des Bodenabtrags and ihre Erfassung in Experiment un Modell. In: Spezielle Prozesse des Bodenabtrags and ihre Erfassung in Experiment un Modell.

Botschek, J., Krause, S., Abel, T., Skowronek, A., 2002a. Hydrological parameterization of piping in loess-rich soils in the Bergisches Land, Nordrhein-Westfalen, Germany. Journal of Plant Nutrition and Soil Science-Zeitschrift für Pflanzenernahrung und Bodenkunde 165, 506-510.

Botschek, J., Krause, S., Abel, T., Skowronek, A., 2002b. Piping and erodibility of loessic soils in Bergisches Land, Nordrhein-Westfalen. Journal of Plant Nutrition and Soil Science-Zeitschrift fur Pflanzenernahrung und Bodenkunde 165, 241-246.

Botschek, J., Maimann, B., Skowronek, A., 2000. Stofftransporte und Reliefformung durch Tunnelerosion im Bergischen Land. Z. Geomorph. N. F. , Suppl. Bd 121, 45-61.

Boucher, S.C. 1995. Management options for acidic sodic soil affected by tunnel erosion. In: Naidu, R., Sumner, M.E., Rengasamy, P. (Eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Publications, Melbourne; 239–246.

Boucher, S.C., 1990. Field Tunnel Erosion Its Characteristics and Amelioration.

Bouma, J., Belmans, C.F.M., Dekker, L.W., 1982. Water infiltration and redistribution in a silt loam subsoil with vertical worm channels. Soil Science Society of America Journal 46, 917-921.

Brisson, E., Demuzere, M., Kwakernaak, B., Van Lipzig, N.P.M., 2011. Relations between atmospheric circulation and precipitation in Belgium. Meteorology and Atmospheric Physics 111, 27-39.

Bryan, R., Price, A., 1980. Recession of the Scarborough Bluffs, Ontario, Canada. Zeitschrift für Geomorphologie, Supp. 34, 48-62.

Bryan, R., Yair, A., 1982. Badland geomorphology and piping. Geo Books (Geo Abstracts Ltd).

Bryan, R.B., 2000. Soil erodibility and processes of water erosion on hillslope. Geomorphology 32, 385-415.

Bryan, R.B., Harvey, L.E., 1985. Observations on the Geomorphic Significance of Tunnel Erosion in A Semiarid Ephemeral Drainage System. Geografiska Annaler Series A-Physical Geography 67, 257-272.

Bryan, R.B., Jones, J.A.A., 1997. The significance of soil piping processes: inventory and prospect. Geomorphology 20, 209-218.

Cammeraat, L.H., 1992. Hydro-geomorphological processes in a small forested catchment: Preferred flow paths of water. dissertation, Universiteit van Amsterdam.

Cancienne, R.M., Fox, G.A., Simon, A., 2008. Influence of seepage undercutting on the stability of root reinforced streambanks. Earth Surf. Process. Landforms 33, 1769-1786.

Carey, S.K., Woo, M.K., 2000. The role of soil pipes as a slope runoff mechanism, Subarctic Yukon, Canada. Journal of Hydrology 233, 206-222.

Carey, S.K., Woo, M.K., 2002. Hydrogeomorphic relations among soil pipes, flow pathways, and soil detachments within a permafrost hillslope. Physical Geography 23, 95-114.

Carling, P.A., 1986. Peat slides in Teesdale and Weardale, northern pennines, july 1983: Description and failure mechanisms. Earth Surf. Process. Landforms 11, 193-206.

Carroll, P. H., 1949. Soil piping in south-eastern Arizona. U.S. Department of Agriculture Regional Bulletin 10, Soil series 13. Soil Conservation Service, Region 6, Albuquerque, New Mexico, 21 pp.

Cerdan, O., Govers, G., Le Bissonnais, Y., Van Oost, K., Poesen, J., Saby, N., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.J.P.M., Raclot, D., Ionita, I., Rejman, J., Rousseva, S., Muxart, T., Roxo, M.J., Dostal, T., 2010. Rates and spatial variations of soil erosion in Europe: A study based on erosion plot data. Geomorphology 122, 167-177.

Cerdan, O., Poesen, J., Govers, G., Saby, N., Le Bissonnais, Y., Gobin, A., Vacca, A., Quinton, J., Auerswald, K., Klik, A., Kwaad, F.P.M., Roxo, M.J., 2006. Sheet and Rill Erosion. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley (J.), Chichester, pp. 501-514.

Chan, K.Y., Heenan, D.P., 1993. Surface Hydraulic-Properties of A Red Earth Under Continuous Cropping with Different Management-Practices. Australian Journal of Soil Research 31, 13-24.

Chapman, P.J., Reynolds, B., Wheater, H.S., 1993. Hydrochemical changes along stormflow pathways in a small moorland headwater catchment in Mid-Wales, UK. Journal of Hydrology 151, 241-265.

Chappell, N.A., 2010. Soil pipe distribution and hydrological functioning within the humid tropics: a synthesis. Hydrol. Process. 24, 1567-1581.

Chappell, N.A., Sherlock, M.D., 2005. Contrasting flow pathways within tropical forest slopes of Ultisol soils. Earth Surf. Process. Landforms 30, 735-753.

Chung, C.J.F., Fabbri, A.G., 1999. Probabilistic prediction models for landslide hazard mapping. Photogrammetric Engineering and Remote Sensing 65, 1389-1399.

Churchman, G.J., Weissman, D.A. 1995. Particle mobility as a parameter in soil dispersibility. In: Naidu, R., Sumner, M.E., Rengasamy, P. (Eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Publications, Melbourne; 191–194.

Closson, D., Engels, P., Demaret, X., 1999. The use of the soil map of Belgium in the assessment of landslide risk. Biotechnology, Agronomy, Society and Environment 3, 165-172.

Colcough, J.D., 1973. Vegetation to control tunnel erosion. Tasmanian Journal of Agriculture 44, 65-70.

Conacher, A.J., Dalrymple, J.B., 1977. The nine unit land surface model: an approach to pedogeomorphic research. Geoderma 18, 1-154.

Coquet, Y., 1998. In situ measurement of the vertical linear shrinkage curve of soils. Soil and Tillage Research 46, 289-299.

Crouch, R.J., 1976. Field tunnel erosion—a review. Soil Conservation Journal, Wagga. Research Centre, pp. 98–111

Crozier, M., 1989. Landslides: Causes, Consequences and Environment. Routledge, London.

Cruden, D.M., Varnes, D.J. 1996. Landslide types and processes. In: Turner, A.K., Schuster, R.L. (Eds.), Landslide Investigation and Mitigation. Transportation Research Board, US National Research Council, Special Report 247, Washington, DC, pp. 36-75.

Culley, J.L.B., Bolton, E.F., 1983. Suspended-Solids and Phosphorus Loads from A Clay Soil .2. Watershed Study. Journal of Environmental Quality 12, 498-503.

Cumberland K.B., 1944. Soil Erosion in New Zealand. Soil Conservation and River Control Council, Wellington, pp. 288.

Czeppe, Z., 1960. Suffosional phenomena in slope loams of the Upper San drainage basin. Instytut Geologiczny Biuletin (Warsaw) 9, 297-232.

Czeppe, Z., 1965. Activity of running water in southwestern Spitsbergen. Geogr. Polon. 6, 141-150.

Dahlke, C., Huisman, J.A., Verachtert, E., André, F., Busch, S., Deckers, J., Moghadas, D., Rings, J., van der Kruk, J., Vanderborght, J, Poesen, J. Detection of soil piping using geophysical methods: a case study in Brakel. *In preparation.*

DEM of Flanders, 2004. DHM Vlaanderen, LIDAR hoogtepunten – brondata, GIS-Vlaanderen, AGIV.

Derbyshire, E.D., Dijkstra, T., Smalley, I.J., 1995. Genesis and properties of collapsible soils. NATO Science Series C, Vol. 468. Kluwer, Amsterdam.

Desmet, P.J.J., Poesen, J., Govers, G., Vandaele, K., 1999. Importance of slope gradient and contributing area for optimal prediction of the initiation and trajectory of ephemeral gullies. Catena 37, 377-392.

Downes, R.G., 1946. Tunnelling erosion in North-Eastern Victoria. Journal of Comm. Science and Ind. Res. 19, 283-292.

Duarte, P., Meneses, R., Hawkins, A.J.S., Zhu, M., Fang, J., Grant, J., 2003. Mathematical modelling to assess the carrying capacity for multi-species culture within coastal waters. Ecol. Modell. 168, 109-143.

Dunne, T., 1990. Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow. In: Higgins, C.G., Coates, D.R. (Eds.), Groundwater Geomorphology, the Role of Subsurface Water in Earth-Surface Processes and Landforms. Geol. Soc. Am. Spec. Pap. 252, pp. 1-28.

Echeverría, M.T., Ibarra, P., Pérez-Cabello, F., 2007. Agricultural land use, piping and gullies activity in the Huerva Lower Valley (Saragossa, Spain). In: Casalí, J., Giménez, R. (Eds.), Progress in Gully Erosion Research.

Edwards, C.A., Bohlen, P.J., 1996. Biology and ecology of earthworms. Chapman and Hall, Dordrecht.

Edwards, G.R., Crawley, M.J., Heard, M.S., 1999. Factors influencing molehill distribution in grassland: implications for controlling the damage caused by molehills. Journal of Applied Ecology 36, 434-442.

Ehlers, W., 1975. Observations on Earthworm Channels and Infiltration on Tilled and Untilled Loess Soil. Soil Science 119, 242-249.

Elsenbeer, H., Lack, A., 1996. Hydrometric and hydrochemical evidence for fast flowpaths at La Cuenca, Western Amazonia. Journal of Hydrology 180, 237-250.

Elsenbeer, H., Lorieri, D., Bonell, M., 1995. Mixing Model Approaches to Estimate Storm Flow Sources in An Overland Flow-Dominated Tropical Rain-Forest Catchment. Water Resources Research 31, 2267-2278.

Elsenbeer, H., Vertessy, R.A., 2000. Stormflow generation and flowpath characteristics in an Amazonian rainforest catchment. Hydrol. Process. 14, 2367-2381.

Emmerson, W.W., 1967. A classification of Soil Aggregates based on their Coherence in Water. Australian Journal of Soil Research, 47 pp.

Evans, A.C., Guild, W.J., 1947. Studies on the relationships between earthworms and soil fertility: I. Biological studies in the field. Annals of Applied Biology 34, 307-330.

Evans, G.L., 1977. Erosion tests on loess silt, Bank Peninsula, New Zealand. Proc. IXth International Conference Soil Mech. & Found. Eng. 2, 63-69.

Evans, G.L., Bell, D.H., 1981. Chemical stabilization of loess, New Zealand. Xth International Conference Soil Mech. & Found. Eng. 649-658.

Evrard, O., Vandaele, K., Bielders, C., van Wesemael, B., 2008. Seasonal evolution of runoff generation on Agricultural land in the Belgian loess belt and implications for muddy flood triggering. Earth Surface Processes and Landforms 33, 1285-1301.

FAO, 1998. FAO, World reference base for soil resources. World Soil Resources Reports 84.

Farifteh, J., Soeters, R., 1999. Factors underlying piping in the Basilicata region, southern Italy. Geomorphology 26, 239-251.

Farres, P.J., Clifford, N.J., White, I.D., 1990. Subsurface Colluviation - An Example from West-Sussex, Uk. Catena 17, 551-561.

Faulkner H. 1990. Vegetation cover density variations and infiltration patterns on piped alkali sodic soils: implications for the modelling of overland flow in semi-arid areas. In Vegetation and Erosion, Thornes JB. (Ed.). John Wiley & Sons Ltd, Chichester; 317–46.

Faulkner, H., 2006. Piping Hazard on Collapsible and Dispersive Soils in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley (J.), Chichester, pp. 537-562.

Faulkner, H., Alexander, R., Teeuw, R., Zukowsky, P., 2004. Variations in soil dispersivity across a gully head displaying shallow sub-surface pipes, and the role of shallow pipes in rill initiation. Earth Surf. Process. Landforms 29, 1143-1160.

Faulkner, H., Alexander, R., Wilson, B.R., 2003. Changes to the dispersive characteristics of soils along an evolutionary slope sequence in the Vera badlands, southeast Spain: implications for site stabilisation. Catena 50, 243-254.

Faulkner, H., Alexander, R., Zukowskyj, P., 2008. Slope-channel coupling between pipes, gullies and tributary channels in the Mocatan catchment badlands, Southeast Spain. Earth Surf. Process. Landforms 33, 1242-1260.

Faulkner, H., Spivey, D., Alexander, R., 2000. The role of some site geochemical processes in the development and stabilisation of three badland sites in Almeria, Southern Spain. Geomorphology 35, 87-99.

Fauzilah, I., Zainab, M., Mukri, M., 2008. A study of the Mechanism of Internal erosion resistance to soil slope instability. Journal of Geotechnical Engineering 13, Bund A, 12 pp.

Feininger, T., 1969. Pseudo-karst on quartz-diorite, Colombia. Zeitschrift für Geomorphologie 13, 115-134

Fitzpatrick, R.W., Boucher, S.C., Naidu, R., Fritsch, E. 1995. Environmental consequence of soil sodicity. In: Naidu, R., Sumner, M.E., Rengasamy, P. (Eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Publications, Melbourne; 163–176.

Fletcher, J.E., Carroll, P.H., 1948. Some properties of soils that are subject to piping in southern Arizona. Soil Sci. Soc. Am. Proc. 13, 545-547.

Fletcher, J.E., Harris, K., Peterson, H.G., Chandler, V.N., 1954. Piping. Trans. Am. Geophys. Union 35, 258-263.

Floyd, E.J., 1974. Tunnel erosion a field study in the Riverina. Journal of theSoil Conservation Service of New South Wales 30, 145-156.

Forsythe, P., 1977. Experiences in identification and treatment of dispersive clays in Mississippi dams. In: Sherard, J.L., Decker, R.S, (Eds.), Dispersive clays, related piping, and erosion in geotechnical projects. ASTM Special Technical Publication, vol 623, pp. 135-155.

Foster, I.D.L., Chapman, A.S., Hodgkinson, R.M., Jones, A.R., Lees, J.A., Turner, S.E., Scott, M., 2003. Changing suspended sediment and particulate phosphorus loads and pathways in underdrained lowland agricultural catchments; Herefordshire and Worcestershire, UK. Hydrobiologia 494, 119-126.

Foster, M., Fell, R., Spannagle, M., 2002. A method for assessing the relative likelihood of failure of embankment dams by piping: reply. Canadian Geotechnical Journal 39, 497-500.

Friend, J.J., Chan, K.Y., 1995. Influence of Cropping on the Population of A Native Earthworm and Consequent Effects on Hydraulic-Properties of Vertisols. Australian Journal of Soil Research 33, 995-1006.

Funmilayo, O., 1977. Distribution and Abundance of Moles (Talpa-Europaea-L) in Relation to Physical Habitat and Food-Supply. Oecologia 30, 277-283.

Gabriels, D., Pauwels, J.M., Deboodt, M., 1977. Quantitative rill erosion study on a loamy sand in the hilly region of Flanders. Earth Surf. Process. Landforms 2, 257-259.

Galarowski, T., 1976. New observations of the present-day suffosion (piping) processes in the Bereznica catchment basin in the Bieszczady Mountains (The East Carpathians). Studia Geomorphologica Carpatho-Balcanica (Krakow) 10,115–122.

Galve, J.P., Bonachea, J., Remondo, J., Gutierrez, F., Guerrero, J., Lucha, P., Cendrero, A., Gutierrez, M., Sanchez, J.A., 2008. Development and validation of sinkhole susceptibility models in mantled karst settings. A case study from the Ebro valley evaporite karst (NE Spain). Engineering Geology 99, 185-197.

Galve, J.P., Gutiérrez, F., Lucha, P., Guerrero, J., Bonachea, J., Remondo, J., Cendrero, A., 2009. Probabilistic sinkhole modelling for hazard assessment. Earth Surf. Process. Landforms 34, 437–452.

Gamba, P., Belotti, V., 2003. Two fast buried pipe detection schemes in Ground Penetrating Radar images. International Journal of Remote Sensing 24, 2467-2484.

García Ruiz, J.M., Lasanta, T., Ortigosa-Izquierdo, L., Arnáez-Vadillo, J., 1986. Pipes in cultivated soils of La Rioja: origin and evolution. Zeitschrift für Geomorphologie Suppl 58, 93–100.

Garcia-Ruíz, J.M., Lasanta, T., 1995. The effects of irrigation on soil piping. A case study in the Ebro depression, Spain. Physics and Chemistry of the Earth 20, 315-320.

Garcia-Ruiz, J.M., Lasanta, T., Alberto, F., 1997. Soil erosion by piping in irrigated fields. Geomorphology 20, 269-278.

Garland, G., Humphrey, B., 1992. Field-Measurements of Discharge and Sediment Yield from A Soil Pipe in the Natal Drakensberg, South-Africa. Zeitschrift für Geomorphologie 36, 15-23.

Geissen, V., Kampichler, C., Llergo-Juarez, J.J.L.D., Galindo-Acantara, A., 2007. Superficial and subterranean soil erosion in Tabasco, tropical Mexico: Development of a decision tree modeling approach. Geoderma 139, 277-287.

Gibbs, H.S. 1945. Tunnel-gully erosion on the Wither Hills, Marlborough, New Zealand. New Zealand Journal of Science and Technology, 27 section A(2): 235-146.

Gibson, J.J., Edwards, T.W.D., Prowse, T.D., 1993. Runoff generation in a high boreal wetland in northern Canada. Nordic Hydrology 24, 213.

Gilman, K., Newson, M., 1980. Soil Pipes and Pipeflow - A Hydrological Study in Upland Wales. Geobooks, Norwich.

Glassey, P.J., 1986. Geotechnical properties of lime stabilized loess, Porth Hills, Canterbury. Unpub. M.Sc Thesis. University of Canterbury, Christchurch.

Gobat, J.M., Aragno, M., Matthey, W., 2004. The Living Soil: fundamentals of soil science and soil biology. Science Publishers, Enfield New Hampshire.

Goldsmith, P.R., Smith, E.H., 1985. Tunnelling soils in south Auckland, New Zealand. Engineering Geology 22, 1-11.

Goossens, D., 1988. Scale Model Simulations of the Deposition of Loess in Hilly Terrain. Earth Surf. Process. Landforms 13, 533-544.

Goossens, D., 1993. The Belgian loess deposits: an overview. In: Goossens, D. (Ed.), Excursion Guide, Geomorphological Processes in the Belgian Loessbelt, Memorial Symposium Prof. Jan De Ploey. Experimental Geomorphology and Landscape Ecosystem Changes. Laboratory for Experimental Geomorphology, K.U. Leuven pp. 5-15.

Goossens, D., 1997. Long-term aeolian loess accumulation modelled in the wind tunnel: The Molenberg case (central loess belt, Belgium). Zeitschrift für Geomorphologie 41, 115-129.

Gorman, M.L., Stone, R.D., 1990. The Natural History of Moles. Comstock, Ithaca, New York.

Govers, G., 1987. Spatial and Temporal Variability in Rill Development Processes at the Huldenberg Experimental Site. Catena Suppl. 8, 17-34.

Govers, G., 1991. Time-dependency of runoff velocity and erosion the effect of the initial soil moisture profile. Earth Surf. Process. Landforms 16, 713-729.

Govers, G., Everaert, W., Poesen, J., Rauws, G., Deploey, J., Lautridou, J.P., 1990. A Long Flume Study of the Dynamic Factors Affecting the Resistance of A Loamy Soil to Concentrated Flow Erosion. Earth Surf. Process. Landforms 15, 313-328.

Grazhdani, S., Jacquin, F., Sulce, S., 1996. Effect of subsurface drainage on nutrient pollution of surface waters in south eastern Albania. Science of the Total Environment 191, 15-21.

Greco, R., Sorriso-Valvo, M., Catalano, E., 2007. Logistic regression analysis in the evaluation of mass movements susceptibility: the Aspromonte case study, Calabria, Italy. Eng. Geol. 89, 47–66.

Gullentops F., 1952. Phénomènes subkarstiques près de Leefdael (Brabant), Bulletin de la Société belge de Géologie 61, 120–124.

Gunn, J., 2000. Introduction. In: Gunn, J. (Ed.), The Geomorphology of Cuilcagh Mountain, Ireland. A Field Guide for the British Geomorphological Research Group Spring Field Meeting. Limestone Research Group, University of Huddersfield, 1-14. (ISBN 186218 030 X)

Gutiérrez, F., 1998. Subsidencia por colapso en un karst aluvial. Análisis de estabilidad. In: Gómez-Ortiz, A., Salvador-Franch, F. (Eds.), Investigaciones recientes de la Geomorfología española. V Reunión Nacional de Geomorfología. Barcelona. pp. 47–58.

Gutierrez, M., Sancho, C., Benito, G., Sirvent, J., Desir, G., 1997. Quantitative study of piping processes in badland areas of the Ebro Basin, NE Spain. Geomorphology 20, 237-253.

Guzzetti, F., Carrara, A., Cardinali, M., Reichenbach, P., 1999. Landslide hazard evaluation: a review of current techniques and their application in a multi-scale study, Central Italy. Geomorphology 31, 181-216.

Guzzetti, F., Reichenbach, P., Ardizzone, F., Cardinali, M., Galli, M., 2006. Estimating the quality of landslide susceptibility models. Geomorphology 81, 166-184.

Hagerty, D.J., 1991a. Piping Sapping Erosion. 1. Basic Considerations. Journal of Hydraulic Engineering 117, 991-1008.

Hagerty, D.J., 1991b. Piping Sapping Erosion. 2. Identification-Diagnosis. Journal of Hydraulic Engineering-Asce 117, 1009-1025.

Hardenbicker, U., 1998. Subterrane Erosion im östlichen Harzvorland. Zeitschrift für Geomorphologie Neue Folge Supplementband 112, 93-103.

Hardenbicker, U., Crozier, M.J., 2002. Soil pipes and slope stability. In: Rybar, J., Stembeck, J., Wagner, P. (Eds.), Landslides. pp. 565-570.

Hardie, M.A., Cotching, W.E., Zund, P.R., 2007. Rehabilitation of field tunnel erosion using techniques developed for construction with dispersive soils. Australian Journal of Soil Research 45, 280-287.

Harvey, A., 1982. The role of piping in the development of badlands and gully systems in south-east Spain. In: Bryan, R., Yair, A. (Eds.), Badland geomorphology and piping. Geobooks: Norwich, pp. 317-336.

Head, K.H., 1982. Manual of Soil Laboratory Testing. Volume 2: Permeability, Shear Strength and Compressibility Tests.

Heede, B.H., 1971. Characteristics and Processes of Soil Piping in Gullies. Transactions-American Geophysical Union 52, 204-&.

Hencher, S.R., 2010. Preferential flow paths through soil and rock and their association with landslides. Hydrol. Process. 24, 1610-1630.

Henn, D., 2002. Tunnelerosion im Bergischen Land – Identifikation, bodenkundlich – geomorphologische Parametrisierung und Ableitung einer Gefährdungskarte. Master thesis, University of Bonn, Germany.

Henn, D., Botschek, J., 2002. Tunnelerosion im Bergischen Land. Identifikation und bodenkundlich – geomorphologische Parametrisierung. In: Spezielle Prozesse des Bodenabtrags and ihre Erfassung in Experiment un Modell. Proceedings 7/8 March 2002, Institut für Bodenkunde, Bonn.

Holden, J., 2004. Hydrological connectivity of soil pipes determined by ground-penetrating radar tracer detection. Earth Surf. Process. Landforms 29, 437-442.

Holden, J., 2005. Controls of soil pipe frequency in upland blanket peat. Journal of Geophysical Research-Earth Surface 110.

Holden, J., 2006. Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. Journal of Geophysical Research-Earth Surface 111.

Holden, J., Burt, T.P., 2002. Piping and pipeflow in a deep peat catchment. Catena 48, 163-199.

Holden, J., Burt, T.P., Vilas, M., 2002. Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. Earth Surf. Process. Landforms 27, 235-249.

Holden, J., Gell, K.F., 2009. Morphological characterization of solute flow in a brown earth grassland soil with cranefly larvae burrows (leatherjackets). Geoderma 152, 181-186.

Hoogerkamp, H., Rogaar, H., Eijsackers, H.J.P., 1983. Effect of earthworms on grassland on recently reclaimed polder soils in the Netherlands. In: Satchell, J. E. (Eds.), Earthworm Ecology: From Darwin to Vermiculture. Chapman and Hall, London, pp. 85-105.

Hosking, P.L., 1967. Tunnelling erosion in New Zealand. J. Soil Water Conserv. 22, 149-151.

Hughes, P.J., 1972. Slope aspect and tunnel erosion in the loess of banks Peninsula, New Zealand. Journal of Hydrology 11, 94-98.

Huisman, J.A., Hubbard, S.S., Redman, J.D., Annan, A.P., 2003. Measuring Soil Water Content with Ground Penetrating Radar: A Review. Vadose Zone Journal 2, 476-491.

Huisman, J.A., Sperl, C., Bouten, W., Verstraten, J.M., 2001. Soil water content measurements at different scales: accuracy of time domain reflectometry and ground-penetrating radar. Journal of Hydrology 245, 48-58.

Hyett, G.A., 1990. The effect of accelerated throughflow on the water yield chemistry under polluted rainfall. PhD dissertation, University of Wales, Aberystwyth, UK.

I.W.O.N.L, 1987. Text Clarifying the Belgian Soil Map, Map Sheet 98E Ronse (in Dutch). Uitgegeven onder de auspiciën van het Instituut tot aanmoediging van het Wetenschappelijk Onderzoek in Nijverheid en Landbouw, Brussels, pp. 163.

IMDC, 2006. Literatuurstudie Faalmechanismen Zeewering – eindrapport, Safecoast.

Imeson, A., 1986. Investigating volumetric changes in clayey soils related to subsurface water movement. Z. Geomorphol. Supp. 60, 115-130.

Imeson, A.C., Kwaad, F.J.P.M., 1980. Gully types and gully prediction. Koninklijk Nederlands Aardrijkskundig Geografisch Tijdschrift 14, 430-441.

Ionita, I., 2006. Gully development in the Moldavian Plateau of Romania. Catena 68, 133-140.

IUSS Working Group WRB, 2007. World Reference Base for Soil Resources 2006, first update 2007. World Soil Resources Reports No. 103. FAO, Rome.

Jackson, J.E. ,1991. A User's Guide to Principal Components. John Wiley, New York, 4-12.

Jackson, R.J., Zealand, N., Bureau, S., 1966. Slips in relation to rainfall and soil characteristics. Journal of Hydrology (New Zealand) 5, 45-53.

Jacobs, P., De Ceukelaire, M., De Breuck, W., De Moor, G., 1999a. Text describing the Belgian Geological Map, Flemish Region, Map Sheet 29 Kortrijk, Map Scale 1/50000 (in Dutch), Ministerie van Economische zaken en Ministerie van de Vlaamse Gemeenschap, Brussels, 68 pp.

Jacobs, P., Van Lancker, V., De Ceukelaire, M., De Breuck, W., De Moor, G., 1999b. Text describing the Belgian Geological Map, Flemish Region, Map Sheet 30 Geraardsbergen, Map Scale 1/50000 (in Dutch), Ministerie van Economische zaken en Ministerie van de Vlaamse Gemeenschap, Brussels, 58 pp.

Jenkins, A., Ashworth, P.J., Ferguson, R.I., Grieve, I.C., Rowling, P., Stott, T.A., 1988. Slope failures in the Ochil Hills, Scotland, November 1984. Earth Surf. Process. Landforms 13, 69-76.

Jermy, C.A., Walker, D.J.H., 1999. Assessing the dispersivity of soils. In: Wardle, G.R., Blight, G.E., Fourie, A.B. (Eds.), Geotechnics for developing Africa. Balkema: Rotterdam, pp. 347-352.

Jones, J., Crane, F., 1984. Pipeflow and pipe erosion in the Maesnant experimental catchment. In: Burt, T., Walling, D. (Eds.), Catchment Experiments in Fluvial Geomorphology. Geobooks, Norwich, pp. 55-72.

Jones, J.A.A., 1971. Soil Piping and Stream Channel Initiation. Water Resources Research 7, 602-610.

Jones, J.A.A., 1981. The Nature of Soil Piping, a Review of Research. Geo Books, Norwich.

Jones, J.A.A., 1982. Experimental studies of pipe hydrology. In: Bryan, R., Yair, A. (Eds.), Badland Geomorphology and Piping. Geo Books, Norwich, pp. 355-370.

Jones, J.A.A., 1986. Some limitations to the a/s index for predicting basin-wide patterns of soil water drainage. Z. Geomorph. N. F. , Suppl. -Bd 60, 7-20.

Jones, J.A.A., 1987a. The Effects of Soil Piping on Contributing Areas and Erosion Patterns. Earth Surf. Process. Landforms 12, 229-248.

Jones, J.A.A., 1987b. The Initiation of Natural Drainage Networks. Progress in Physical Geography 11, 207-245.

Jones, J.A.A., 1994. Soil Piping and Its Hydrogeomorphic Function. Cuaternario y Geomorfologia 8, 77-102.

Jones, J.A.A., 1997a. Pipeflow contributing areas and runoff response. Hydrol. Process. 11, 35-41.

Jones, J.A.A., 1997b. The role of natural pipeflow in hillslope drainage and erosion: extrapolating from the Maesnant data. Physics and Chemistry of the Earth 22, 303-308.

Jones, J.A.A., 2004a. Implications of natural soil piping for basin management in upland Britain. Land Degradation & Development 15, 325-349.

Jones, J.A.A., 2004b. Pipe and Piping. In: Goudie, A.S. (Ed.), Encyclopedia of geomorphology. Routledge, pp. 784-788.

Jones, J.A.A., 2010. Soil piping and catchment response. Hydrol. Process. 24, 1548-1566.

Jones, J.A.A., Connelly, L.J., 2002. A semi-distributed simulation model for natural pipeflow. Journal of Hydrology 262, 28-49.

Jones, J.A.A., Cottrell, C.I., 2007. Long-term changes in stream bank soil pipes and the effects of afforestation. Journal of Geophysical Research-Earth Surface 112.

Jones, J.A.A., Richardson, J.M., Jacob, H.J., 1997. Factors controlling the distribution of piping in Britain: a reconnaissance. Geomorphology 20, 289-306.

Kerényi, A., 1994. Loess erosion on the Tokaj Big-Hill. Quaternary International 24, 47-52.

Knapen, A., Poesen, J., 2010. Soil erosion resistance effects on rill and gully initiation points and dimensions. Earth Surf. Process. Landforms 35, 217-228.

Knapen, A., Poesen, J., De Baets, S., 2007. Seasonal variations in soil erosion resistance during concentrated flow for a loess-derived soil under two contrasting tillage practices. Soil & Tillage Research 94, 425-440.

Kronvang, B., Laubel, A., Grant, R., 1997. Suspended sediment and particulate phosphorus transport and delivery pathways in an arable catchment, Gelbaek Stream, Denmark. Hydrol. Process. 11, 627-642.

Krothe, N. C., Fei, Y., 1999. Polychlorinated biphenyl (PCB) contamination of a karst aquifer in an urban environment, central Indiana, USA. In: Chilton, J. (Ed.). Ground water in the urban environment (Selected city profies, 21), 171-179.

Laffan, M.D., Cutler, E.J.B., 1977. Landscapes, Soils, and Erosion of A Catchment in Wither Hills, Marlborough .2. Mechanism of Tunnel-Gully Erosion in Wither Hill Soils from Loessial Drift and Comparison with Other Loessial Soils in South Island. New Zealand Journal of Science 20, 279-289.

Langohr, R., Crombé, P., 1999. Valkuilen voor archeologen. Natuur en Techniek 67 (6), 78-85.

Lasko, T.A., Bhagwat, J.G., Zou, K.H., Ohno-Machado, L., 2005. The use of receiver operating characteristic curves in biomedical informatics. J. Biomedical Informatics 38, 404-415.

Leonards, G.A., Huang, A.B., Ramos, J., 1991. Piping and Erosion Tests at Conner Run Dam. Journal of Geotechnical Engineering 117, 108-117.

Levy, G.J., 2000. Sodicity. In: Sumner M.E. (ed.) Handbook of Soil Science. CRC Press, Boca Raton, Fl., G27-G64.

Ligthart, T.N., 1996. Development of earthworm burrow systems and the influence of earthworms on soil hydrology. dissertation, Wageningen University.

Ligthart, T.N., Peek, G.J.C.W., 1997. Evolution of earthworm burrow systems after inoculation of lumbricid earthworms in a pasture in the Netherlands. Soil Biology & Biochemistry 29, 453-462.

Lim, S.S. 2006. Experimental Investigation of erosion in variably saturated clay soils. PhD Thesis. School of Civil and Environmental Engineering. The University of New South Wales.

López Bermúdez, F., Romero Díaz, M.A., 1989. Piping erosion and badland development in southeast Spain. Catena Suppl. 14, 59-73.

Lundekvam, H.E., 2007. Plot studies and modelling of hydrology and erosion in southeast Norway. Catena 71, 200-209.

Lundekvam, H., Skoien, S., 1998. Soil erosion in Norway. An overview of measurements from soil loss plots. Soil Use and Management 14, 84-89.

Lundgren, L., 1978. Studies of Soil and Vegetation Development on Fresh Landslide Scars in the Mgeta Valley, Western Uluguru Mountains, Tanzania. Geogr. Ann. 60A, 91-127.

Maillol, J.M., Seguin, M.K., Gupta, O.P., Akhauri, H.M., Sen, N., 1999. Electrical resistivity tomography survey for delineating uncharted mine galleries in West Bengal, India. Geophysical Prospecting 47, 103-116.

Malamud, B.D., Turcotte, D.L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties. Earth Surf. Process. Landforms 29, 687-711.

Malicki, A. 1935. Przyczynek do znajomosci zjawisk krasowych w obszarze lessowym. Czasopismo Geograficzne, Lwów 2-4(13), 328-335.

Malinowski, J., 1963. Uwagi o wspol czynniku makroporowatosci lessow w Polsce. Biuletyn Instytutu Geologicznego (Poland) 182(2), 5-24.

Marshall, A.F., Workman, J.P., 1977. Identification of dispersive clays in the Texas Gulf coast area. ASTM special technical publication 623, 274-286.

Mather, A.E., Griffiths, J.S., Stokes, M., 2003. Anatomy of a 'fossil' landslide from the Pleistocene of SE Spain. Geomorphology 50, 135-149.

McCaig, M., 1983. Contributions to storm quickflow in a small headwater catchment - the role of natural pipes and soil macropores. Earth Surf. Process. Landforms 8, 239-252.

McDonnell, J.J., 1990. The influence of macropores on debris flow initiation. Quarterly Journal of Engineering Geology and Hydrogeology 23, 325.

McDonnell, J.J., Taratoot, M., 1995. Soil Pipe Effects on Pore Pressure Redistribution in Low Permeability Soils. Geotechnical Engineering 26, 53-62.

McIntosh, P., Laffan, M., 2005. Soil erodibility and erosion hazard: Extending these cornerstone soil conservation concepts to headwater streams in the forestry estate in Tasmania. Forest Ecology and Management 220, 128-139.

McNeill, 1980. Electromagnetic terrain conductivity measurement at low induction numbers. Geonics Technical Note TN-6, 15 pp.

Mitchell, J.K., 1993. Fundamentals of soil behavior. 2nd Edition, John Wiley & Sons. pp. 111-130, 208-212.

Mochales, T., Casas, A., Pueyo, E., Pueyo, O., Román, M., Pocoví, A., Soriano, M., Ansón, D., 2008. Detection of underground cavities by combining gravity, magnetic and ground penetrating radar surveys: a case study from the Zaragoza area, NE Spain. Environmental Geology 53, 1067-1077.

Montgomery, D.R., 1994. Road Surface Drainage, Channel Initiation, and Slope Instability. Water Resources Research 30, 1925-1932.

Montgomery, D.R., Dietrich, W.E., 1994. Landscape Dissection and Drainage Area-Slope Threshold. In: Kirkby, M.J. (Ed.), Process Models and Theoretical Geomorphology. John Wiley & Sons Ltd, pp. 221-246.

Moore, I.D., Burch, G.J., Mackenzie, D.H., 1988. Topographic Effects on the Distribution of Surface Soil-Water and the Location of Ephemeral Gullies. Transactions of the Asae 31, 1098-1107.

Mualem, Y., Assouline, S., 1992. Flow processes in sealing soils: conceptions and solutions. In: Sumner, B.A., Stewart, M.E. (Eds.), Soil Crusting: chemical and physical processes. pp. 123-150. Lewis Publishers

Muttuel, T., 2008. Erosion rate of chemically stabilized soils incorporating tensile stress-deformation behaviour. PhD Thesis. School of Civil, Mining Environmental Engineering. University of Wollongong.

Nachtergaele, J., Poesen, J., 2002. Spatial and temporal variations in resistance of loess-derived soils to ephemeral gully erosion. European Journal of Soil Science 53, 449-463.

Nachtergaele, J., Poesen, J., Steegen, A., Takken, I., Beuselinck, L., Vandekerckhove, L., Govers, G., 2001. The value of a physically based model versus an empirical approach in the prediction of ephemeral gully erosion for loess-derived soils. Geomorphology 40, 237-252.

Nadal-Romero, E., Verachtert, E., Poesen, J., 2009. Pinhole test for identifying susceptibility of soils to piping erosion: effect of water quality and Hydraulic head. In: Romero-Díaz, A., Belmonte-Serrato, F., Alonso-Sarria, F., López-Bermúdez, F. (Eds.), Advances in studies on desertification. Contributions to the International Conference on Desertification in memory of professor John B. Thornes. Murcia, pp. 351-354.

Nadal-Romero, E., Verachtert, E., Maes, R., Poesen, J. 2011. Quantitative assessment of the piping erosion susceptibility of loess-derived soil horizons using the pinhole test. Geomorphology, accepted.

Naidu, R., Sumner, M.E., Rengasamy, P. 1995. Australian Sodic Soils: Distribution, Properties and Management. CSIRO Publications Melbourne.

Neal, C., Rosier, P.T.W., 1990. Chemical studies of chloride and stable oxygen isotopes in two conifer afforested and moorland sites in the British uplands. Journal of Hydrology 115, 269-283.

Newman, J.C., Phillips, J.R.H. 1957. Tunnel erosion in the Riverina. J. Soil Conserv. Serv. New South Wales 13, 159-169.

Nieber, J.L., Steenhuis, T.S., Walter, T., Bakker, M., 2006. Enhancement of seepage and lateral preferential flow by biopores on hillslopes. Biologia 61, S225-S228.

Noguchi, S., Tsuboyama, Y., Sidle, R.C., Hosoda, I., 1999. Morphological characteristics of macropores and the distribution of preferential flow pathways in a forested slope segment. Soil Science Society of America Journal 63, 1413-1423.

Noguchi, S., Tsuboyama, Y., Sidle, R.C., Hosoda, I., 2001. Subsurface runoff characteristics from a forest hillslope soil profile including macropores, Hitachi Ohta, Japan. Hydrol. Process. 15, 2131-2149.

Norrström, A.C., Jacks, G., 1996. Water pathways and chemistry at the groundwater/surface water interface to Lake Skjervatjern, Norway. Water Resour. Res. 32, 2221-2229.

Nuutinen, V., Butt, K.R., 2003. Interaction of Lumbricus terrestris L. burrows with field subdrains. Pedobiologia 47, 578-581.

Ogg, J.G., Ogg, G., Gradstein, F.M., 2008. The Concise Geologic Time Scale. Cambridge, Cambridge University Press. ISBN: 9780521898492.

Oh, S., Sun, C.G., 2008. Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam. Environmental Geology 54, 31-42.

Ost, L., Van Den Eeckhaut, M., Poesen, J., Vanmaercke-Gottigny, M.C., 2003. Characteristics and spatial distribution of large landslides in the Flemish Ardennes (Belgium). Zeitschrift für Geomorphologie 47, 329-350.

Øygarden, L., Kvaerner, J., Jenssen, P.D., 1997. Soil erosion via preferential flow to drainage systems in clay soils. Geoderma 76, 65-86.

Park, S., Kim, C., Son, J.S., Yi, M.J., Kim, J.H., 2009. Detection of cavities in a karst area by means of a 3D electrical resistivity technique. Exploration Geophysics 40, 27-32.

Parker, G.G., 1963. Piping, a geomorphic agent in land-form development of the drylands. In: Land Erosion, Precipitation, Hydrometry, Soil Moisture. pp. 103-113.

Parker, G.G., Higgins, C.G., Wood, W.W., 1990. Piping and pseudokarst in drylands. In: Higgins, C.G., Coates, D.R. (Eds.), Groundwater Geomorphology: The Role of Subsurface Water in Earth-Surface Processes and Landforms. Geological Society of America, Boulder, Colorado, pp. 77-110.

Parker, G.G., Jenne, E.A., 1967. Structural failure of western highways caused by piping. Highway Research Record.

Peele, T.C., Beale, O.W., Latham, E.E., 1938. The effect of lime and organic matter on the erodibility of Cecil clay. Soil Science Society of America Proceedings 3, 289-295.

Pettinelli, E., Di Matteo, A., Mattei, E., Crocco, L., Soldovieri, F., Redman, J.D., Annan, A.P., 2009. GPR Response From Buried Pipes: Measurement on Field Site and Tomographic Reconstructions. IEEE Transactions on Geoscience and Remote Sensing IEEE 47, 2639-2645.

Piccarreta, M., Faulkner, H., Bentivenga, M., Capolongo, D., 2006. The influence of physico-chemical material properties on erosion processes in the badlands of Basilicata, Southern Italy. Geomorphology 81, 235-251.

Pickard, J., 1999. Tunnel erosion initiated by feral rabbits in gypsum, semi-arid New South Wales, Australia. Zeitschrift fur Geomorphologie 43, 155-166.

Pierson, T.C., 1983. Soil pipes and slope stability. Quarterly Journal of Engineering Geology & Hydrogeology 16, 1.

Pilgrim, D.H., Huff, D.D., 1983. Suspended Sediment in Rapid Subsurface Stormflow on A Large Field Plot. Earth Surf. Process. Landforms 8, 451-463.

Poesen, J., 1989. Conditions for gully formation in the Belgian loam belt and some ways to control them. Soil Technology Series 1, 39-52.

Poesen, J., 1993. Gully typology and gully control measures in the European Loess Belt. In: Wicherek, S. (Ed.), Farm Land Erosion in Temperate Plains Environments and Hills. Elsevier, Amsterdam, pp. 221-239.

Poesen, J., Govers, G., 1990. Gully erosion in the loam belt of Belgium: typology and control measures. In: Boardman, J., Foster, I.D.L., Dearing, J.A. (Eds.), Soil Erosion on Agricultural Land. Wiley, Chichester, pp. 513-530.

Poesen, J., Govers, G., 1994. Bodemerosie in Midden-België. Een stand van zaken. Onze Alma Mater 48, 251-267.

Poesen, J., Ingelmosanchez, F., Mucher, H., 1990. The Hydrological Response of Soil Surfaces to Rainfall As Affected by Cover and Position of Rock Fragments in the Top Layer. Earth Surf. Process. Landforms 15, 653-671.

Poesen, J., Nachtergaele, J., Verstraeten, G., Valentin, C., 2003. Gully erosion and environmental change: importance and research needs. Catena 50, 91-133.

Poesen, J., Vandaele, K., van Wesemael, B., 1996. Contribution of gully erosion to sediment production on cultivated lands and rangelands. In: Erosion and Sediment Yield: Global and Regional Perspectives. pp. 251-266.

Poesen, J., Vandaele, K., van Wesemael, B., 1998. Gully erosion: importance and model implications. In: Boardman, J., Favis-Mortlock, D. (Eds.), Modelling Soil Erosion by water. Springer-Berlag, Berlin, pp. 285-311

Poesen, J., Vanwalleghem, T., de Vente, J., Knapen, A., Verstraeten, G., Martínez-Casasnovas, J.A., 2006. Gully erosion in Europe. In: Boardman, J., Poesen, J. (Eds.), Soil Erosion in Europe. Wiley (J.), Chichester, pp. 515-536.

Premchitt, J., Brand, E.W., Phillipson, H.B., 1986. Landslides caused by rapid groundwater changes. Geological Society, London, Engineering Geology Special Publications 3, 87.

Putty, M.R.Y., Prasad, R., 2000. Runoff processes in headwater catchments--an experimental study in Western Ghats, South India. Journal of Hydrology 235, 63-71.

Pye, K., 1984. Loess. Progress in Physical Geography 8, 176-217.

Quinton, W.L., Marsh, P., 1998. The influence of mineral earth hummocks on subsurface drainage in the continuous permafrost zone. Permafrost and Periglacial Processes 9, 213-228.

Quirk, J.P., Schofield, R.K., 1955. The effect of electrolyte concentration on soil permeability. Australian Journal of Soil Research 6, 163-178.

Rahimi, H., Abbasi, N., 2008. Failure of concrete canal lining on fine sandy soils: a case study for the Saveh project. Irrigation and Drainage 57, 83-92.

Reeves, G.M., Simms, I., Cripps, J.C., 2006. Clay materials in Construction. Geological Society Engineering Geology. Special Publication 21. AA Balkema.

Rengasamy, P., Greene, R.S.B., Ford, G.W., Mehanni, A.H., 1984. Identification of dispersive behaviour and the management of red-brown earths. Australian Journal of Soil Research 22, 413-431.

Richards, L.R., Cowland, J.W., 1986. Stability evaluation of some urban rock slopes in a transient groundwater regime. In: Proceedings of the Conference on Rock Engineering and Excavation in an Urban Environment, IMM, Hong Kong, 357–363.

Richards, K.S., Reddy, K.R., 2007. Critical appraisal of piping phenomena in earth dams. Bulletin of Engineering Geology and the Environment 66, 381-402.

Rodzik, J., Furtak, T., Zglobicki, W., 2009. The impact of snowmelt and heavy rainfall runoff on erosion rates in a gully system, Lublin Upland, Poland. Earth Surf. Process. Landforms 34, 1938-1950.

Romero Díaz A., Plaza Martínez, J.F., A., Sánchez Soriano, A., Belmonte Serrato, F., Ruiz Sinoga, J.D., 2009. Estimated volume of soil lost by piping erosion processes. Southeastern Spain. In: Romero Díaz A., Belmonte Serrato F., Alonso Sarria F., López Bermúdez F. (Eds.), Advances in studies on desertification. Contributions to the International Conference On Desertification In Memory Of Professor John B. Thornes, Murcia, Spain, September 16-19. (ISBN 978-84-9371-888-9) p.403-406.

Romero Díaz, A., Marín Sanelandro, P., Sánchez Soriano, A., 2007b. Surfaces of gullies generates by piping process in abandoned fields (South-East of Spain). In: Casalí, J., Giménez, R. (Eds.), Progress in Gully Erosion Research.

Romero Díaz, A., Marín Sanelandro, P., Sánchez Soriano, A., Belmonte Serrato, F., Faulkner, H., 2007a. The causes of piping in a set of abandoned agricultural terraces in southeast Spain. Catena 69, 282-293.

Rooyani, F., 1985. A Note on Soil Properties Influencing Piping At the Contact Zone Between Albic and Argillic Horizons of Certain Duplex Soils (Aqualfs) in Lesotho, Southern Africa. Soil Science 139, 517-522.

Russell, M.A., Walling, D.E., Hodgkinson, R.A., 2001. Suspended sediment sources in two small lowland agricultural catchments in the UK. Journal of Hydrology 252, 1-24.

Ruysschaert, G., Poesen, J., Notebaert, B., Verstraeten, G., Govers, G., 2008. Spatial and long-term variability of soil loss due to crop harvesting and the importance relative to water erosion: A case study from Belgium. Agriculture Ecosystems & Environment 126, 217-228.

Ruysschaert, G., Poesen, J., Verstraeten, G., Govers, G., 2004. Soil loss due to crop harvesting: significance and determining factors. Progress in Physical Geography 28, 467-501.

SAS Institute, 1994. SAS user’s guide. SAS Inst., Cary

Schafer, G.J., 1978. Pinhole Test for Dispersive Soil-Suggested Change. Technical Notes, 760-765.

Scholz, H., Strohmenger, M. 1999. Dolinenartige Sackungsstrukturen in den Molassebergen des südwestbayerischen Alpenvorlandes. – Jber. u. Mitt. oberrhein. Geol. Ver., N.F. 81, 275-283.

Sekera, F., Brunner, A., 1943. Beitráge zur Methodik der Gareforschung. Z. Pflanzenernähr. Bodenkd. 29, 169-212.

Selby, M.J., 1993. Hillslope materials and processes. Oxford University Press, Oxford.

Sharma, R.H., Konietzky, H., 2011. Instrumented failure of hillslope models with soil-pipes. Geomorphology 130, 272-279.

Sherard, J.L., Decker, R.S. 1976. Dispersive Clays, Related Piping, and Erosion in Geotechnical Projects. ASTM Special Technical Publication 623. American Society for Testing and Materials, Philadelphia, PA.

Sherard, J.L., Dunningan, L., Decker, R.S., Steele, F., 1976a. Pinhole test for identifying dispersive soils. Journal of the Geotechnical Engineering Division 102, 69-85.

Sherard, J.L., Decker, R.S., Dunningan, L., 1976b. Identification and nature of dispersive soils. Journal of the Geotechnical Engineering Division, 102, 287-301.

Sherard, J.L., Decker, R.S., Ryker, N.L., 1972. Piping in Earth Dams of Dispersive Clay. Proceedings, ASCE Specialty Conference on the Performance of Earth and Earth-Supported Structures 1, 589-626.

Sidle, R.C., Kitahara, H., Terajima, T., Nakai, Y., 1995. Experimental Studies on the Effects of Pipeflow on Throughflow Partitioning. Journal of Hydrology 165, 207-219.

Sidle, R.C., Pearce, A.J., O'Loughlin, C.L., 1985. Hillslope stability and land use. Amer Geophysical Union.

Silva, W., van Velzen, E., 2008. De dijk van de toekomst? : quick scan doorbraakvrije dijken. Rijkswaterstaat Waterdienst WD rapport (2008.052), Deltares (Q4558.32). Ministerie van Verkeer en Waterstaat, 83 pp.

Sklash, M.G., Beven, K.J., Gilman, K., Darling, W.G., 1996. Isotope studies of pipeflow at Plynlimon, Wales, UK. Hydrol. Process. 10, 921-944.

Smets, T., 2009. Effectiveness of biological geotextiles in controlling soil erosion by water at a range of spatial scales. Unpublished PhD thesis, Division of Geography, K.U. Leuven, Belgium.

Smith, R.J., 2009. Use and Misuse of the Reduced Major Axis for Line-Fitting. American Journal of Physical Anthropology 140, 476-486.

So, H.B., 2002. Slaking, dispersion, and crust formation. In: Lal, R. (Eds.), Encyclopedia of Soil Science. Marcel Dekker, New York, pp. 1206-1209.

Sogon, S., Penven, M.J., Bonte, P., Muxart, T., 1999. Estimation of sediment yield and soil loss using suspended sediment load and Cs-137 measurements on agricultural land, Brie Plateau, France. Hydrobiologia 410, 251-261.

Soldovieri, F., Prisco, G., Persico, R., 2008. Application of Microwave Tomography in Hydrogeophysics: Some Examples. Vadose Zone J. 7, 160-170.

Starkel, l., 1960. Rozwój rzeźby Karpat fliszowych w holocenie. Prace geogr. IGPAN 22, Warszawa, pp. 293.

Sumner, M.E. 1992. The electrical double layer and soil dispersion. In: Sumner, M. E., Stewart, B.A. (Eds), Soil Crusting: Chemical and Physical Processes. Lewis, Boca Raton; 1–34.

Sumner, M.E., Naidu, R., 1997. Sodic Soils. Oxford University Press, New York, NY.

Sumner, M.E., Stewart, B.A. 1992. Soil Crusting: chemical and physical processes. Lewis, Boca Raton, FL.

Swets, J.A., 1988. Measuring the accuracy of diagnostic systems. Science 240, 1285–1293.

Tada, Y., Okumura, T., Kubota, T., 2002. Examination of the influence of soil pipes on slope failure. Journal of the Japan Society of Erosion Control Engineering 55, 12-20.

Takken, I., Croke, J., Lane, P., 2008. Thresholds for channel initiation at road drain outlets. Catena 75, 257-267.

Temple, P., Rapp, A., 1972. Landslides in the Mgeta area, western Uluguru Mountains: Geomorphological effects of sudden heavy rainfall. Geogr. Ann. 54A, 157-93.

Terajima, T., Sakamoto, T., Shirai, T., 2000. Morphology, structure and flow phases in soil pipes developing in forested hillslopes underlain by a Quaternary sand-gravel formation, Hokkaido, northern main island in Japan. Hydrol. Process. 14, 713-726.

Terzaghi, K., Peck, R.B., 1966. Soil Mechanics in Engineering Practice. John Wiley & Sons Inc. New York.

Topp, G., Davis, J., Annan, A., 1980. Electromagnetic determination of soil-water content - Measurements in coaxial transmission lines. Water Resour. Res. 16, 574-582.

Torri, D., Bryan, R., 1997. Micropiping processes and biancana evolution in southeast Tuscany, Italy. Geomorphology 20, 219-235.

Torri, D., Colica, A., Rockwell, D., 1994. Preliminary-Study of the Erosion Mechanisms in A Biancana Badland (Tuscany, Italy). Catena 23, 281-294.

Tosun, H., 1997. Comparative study on physical tests of dispersibility of soils used for earthfill dams in Turkey. Geotechnical Testing Journal 20, 242-251.

Tsukamoto, Y., Ohta, T., Noguchi, H., 1982. Hydrological and geomorphological studies of debris slides on forested hillslopes in Japan. Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield, IAHS Publ 137, 89-98.

Turner, M.L., Greene, R.S.B., Knackstedt, M., Senden, T.J., Sakellariou, A., White, I., 2008. Use of gamma emission CT to study the effect of electrolyte concentration on regions of preferred flow and hydraulic conductivity in deep regolith materials. Australian Journal of Soil Research 46, 101-111.

Turtola, E., Alakukku, L., Uusitalo, R., Kaseva, A., 2007. Surface runoff, subsurface drainflow and soil erosion as affected by tillage in a clayey Finnish soil. Agricultural and Food Science 16, 332-351.

Turtola, E., Paajanen, A., 1995. Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. Agricultural Water Management 28, 295-310.

Turton, D.J., Barnes, D.R., Navar, J.D., 1995. Old and new water in subsurface flow from a forest soil block. Journal of Environmental Quality 24, 139-146.

Uchida, T., 2004. Clarifying the role of pipe flow on shallow landslide initiation. Hydrol. Process. 18, 375-378.

Uchida, T., Kosugi, K., Mizuyama, T., 1999. Runoff characteristics of pipeflow and effects of pipeflow on rainfall-runoff phenomena in a mountainous watershed. Journal of Hydrology 222, 18-36.

Uchida, T., Kosugi, K., Mizuyama, T., 2001. Effects of pipeflow on hydrological process and its relation to landslide: a review of pipeflow studies in forested headwater catchments. Hydrol. Process. 15, 2151-2174.

Ulén, B., Persson, K., 1999. Field scale phosphorus losses from a drained clay soil in Sweden. Hydrol. Process. 13, 2801-2812.

Vacher, C. A., Loch, R. J., Raine, S. R., 2004a. Identification and management of dispersive mine spoils. Australian Centre of Mining Environmental Research, Landloch Pty Ltd.

Vacher, C.A., Raine, S.R., Loch, R.J., 2004b. Testing procedures to characterise tunnelling risk on spoil materials. In: Conserving Soil and Water for Society: Sharing Solutions.

Van Dam, R.L., Schlager, W., Dekkers, M.J., Huisman, J.A., 2002. Iron oxides as a cause of GPR reflections. Geophysics 67, 536-545.

Van de Wauw, J., Finke, P., 2010. Methods for updating the drainage class map in Flanders, Belgium. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Van Den Eeckhaut, M., 2006. Spatial and temporal patterns of landslides in hilly regions. The Flemish Ardennes (Belgium). PhD dissertation, Department Geography-Geology, K.U.Leuven.

Van Den Eeckhaut, M., Marre, A., Poesen, J., 2010a. Comparison of two landslide susceptibility assessments in the Champagne-Ardenne region (France). Geomorphology 115, 141-155.

Van Den Eeckhaut, M., Poesen, J., Govers, G., Verstraeten, G., Demoulin, A., 2007a. Characteristics of the size distribution of recent and historical landslides in a populated hilly region. Earth and Planetary Science Letters 256, 588-603.

Van Den Eeckhaut, M., Poesen, J., Vandekerckhove, L., Van Gils, M., Van Rompaey, A., 2010. Human-environment interactions in residential areas susceptible to landsliding: the Flemish Ardennes case study. Area 42, 339-358.

Van Den Eeckhaut, M., Poesen, J., Verstraeten, G., Vanacker, V., Moeyersons, J., Nyssen, J., van Beek, L.P.H., 2005. The effectiveness of hillshade maps and expert knowledge in mapping old deep-seated landslides. Geomorphology 67, 351-363.

Van Den Eeckhaut, M., Poesen, J., Verstraeten, G., Vanacker, V., Nyssen, J., Moeyersons, J., van Beek, L.P.H., Vandekerckhove, L., 2007b. Use of LIDAR-derived images for mapping old landslides under forest. Earth Surf. Process. Landforms 32, 754-769.

Van Den Eeckhaut, M., Vanwalleghem, T., Poesen, J., Govers, G., Verstraeten, G., Vandekerckhove, L., 2006. Prediction of landslide susceptibility using rare events logistic regression: A case-study in the Flemish Ardennes (Belgium). Geomorphology 76, 392-410.

van Dijk, A.I.J.M., Keenan, R.J., 2007. Planted forests and water in perspective. Forest Ecology and Management 251, 1-9.

van Eekeren, N., Bommele, L., Bloem, J., Schouten, T., Rutgers, M., de Goede, R., Reheul, D., Brussaard, L., 2008. Soil biological quality after 36 years of ley-arable cropping, permanent grassland and permanent arable cropping. Applied Soil Ecology 40, 432-446.

Van Hoestenberghe, T., Huygens, M., Peeters, P., Mostaert, F., 2010. Opstellen bresgroeiparameters Vlaamse rivierdijken: deelopdracht 1. Literatuurstudie bresgroeiproces. versie 2.0. WL Rapporten, 706_08c. Waterbouwkundig Laboratorium/Soresma: Antwerpen. VI, 90 pp.

Van Oost, K., Govers, G., Desmet, P., 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. Landscape Ecology 15, 577-589.

van Schoor, M., 2002. Detection of sinkholes using 2D electrical resistivity imaging. Journal of applied geophysics 50, 393-399.

Vanacker, V., Vanderschaeghe, M., Govers, G., Willems, E., Poesen, J., Deckers, J., De Bievre, B., 2003. Linking hydrological, infinite slope stability and land-use change models through GIS for assessing the impact of deforestation on slope stability in high Andean watersheds. Geomorphology 52, 299-315.

Vandaele, K., Poesen, J., Govers, G., vanWesemael, B., 1996. Geomorphic threshold conditions for ephemeral gully incision. Geomorphology 16, 161-173.

Vandekerckhove, L., Poesen, J., Wijdenes, D.O., Gyssels, G., Beuselinck, L., de Luna, E., 2000. Characteristics and controlling factors of bank gullies in two semi-arid mediterranean environments. Geomorphology 33, 37-58.

Vanderputten, F., 2006. L'érosion souterraine dans la vallée de la Gueule. Master thesis. Faculté d’ingénierie biologique, agronomique et environnementale. Université catholique de Louvain, Louvain-la-Neuve.

Vanmaercke-Gottigny, M.C., 1995. Detailed geomorphological mapping as a scientific investigation method, a case study: the maps ‘Geraardsbergen’ and ‘Kortrijk’. PhD thesis, Faculty for Sciences, V.U.B., Brussels.

Vanwalleghem, T., Poesen, J., Nachtergaele, J., Verstraeten, G., 2005. Characteristics, controlling factors and importance of deep gullies under cropland on loess-derived soils. Geomorphology 69, 76-91.

Vanwalleghem, T., Van Den Eeckhaut, M., Poesen, J., Deckers, J., Nachtergaele, J., Van Oost, K., Slenters, C., 2003. Characteristics and controlling factors of old gullies under forest in a temperate humid climate: a case study from the Meerdaal Forest (Central Belgium). Geomorphology 56, 15-29.

Vanwalleghem, T., Van Den Eeckhaut, M., Poesen, J., Govers, G., Deckers, J., 2008. Spatial analysis of factors controlling the presence of closed depressions and gullies under forest: Application of rare event logistic regression. Geomorphology 95, 504-517.

Verstraeten, G., Van Oost, K., Van Rompaey, A., Poesen, J., Govers, G., 2002. Evaluating an integrated approach to catchment management to reduce soil loss and sediment pollution through modelling. Soil Use and Management 18, 386-394.

Verstraeten, W.W., Muys, B., Feyen, J., Veroustraete, F., Minnaert, M., Meiresonne, L., De Schrijver, A., 2005. Comparative analysis of the actual evapotranspiration of Flemish forest and cropland, using the soil water balance model WAVE. Hydrology and Earth System Sciences 9, 225–241.

Vieira, B.C., Fernandes, N.F., 2004. Landslides in Rio de Janeiro: The role played by variations in soil hydraulic conductivity. Hydrol. Process. 18, 791-805.

Walsh, R.P.D., Howells, K.A., 1988. Soil pipes and their role in runoff generation and chemical denudation in a humid tropical catchment in Dominica. Earth Surf. Process. Landforms 13, 9-17.

Ward, A.J., 1966. Pipe/shaft phenomena in Northland. Journal of Hydrology (New Zealand) 5, 72.

Warsta, L., Paasonen-Kivekäs, M., Karvonen T., Taskinen, A., 2009. Modelling surface and subsurface flow of water and erosion at clayey, subsurface drained agricultural field. In: Anderssen RS, Braddock RD, Newham LTH (Eds.). 18th

World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, and International Association for Mathematics and Computers in Simulation, July 2009, pp. 1901-1907. ISBN: 978-0-9758400-7-8. http://www.mssanz.org.au/modsim09/F3/warsta.pdf

Weyman, D.R., 1974. Runoff processes, contributing area and streamflow in a small upland catchment. In: Gregory, K.J., Walling, D.E. (Eds.), Fluvial Processes in Instrumented Watersheds. British Geomorphological Research Group Special Publication, 6, pp. 1433-1443.

Whaler, M., Arulanandan, K., 1976. Evaluation of pinhole test. Technical Report, Dept. of Civil Engng, University of California, Davis.

Wilson, C.M., Smart, P.L., 1984. Pipes and pipe flow process in an upland catchment, Wales. Catena 11, 145-158.

Wilson, G., 2011. Understanding soil-pipe flow and its role in ephemeral gully erosion. Hydrol. Process. 25, 2354-2364.

Wilson, G.V., Periketi, R.K., Fox, G.A., Dabney, S.M., Shields, F.D., Cullum, R.F., 2007. Soil properties controlling seepage erosion contributions to streambank failure. Earth Surf. Process. Landforms 32, 447-459.

Woodruff, J.F., 1971. Debris Avalanches as an Erosional Agent in the Appalachian Mountains. Journal of Geography 70, 399-406.

Yetton, M.D., 1986. Investigation and remedial measures for subsurface erosion control in Bank Peninsula loess. Unpub. M.Sc (Eng. Geol) Thesis. University of Canterbury, Christchurch.

Zaitlin, B., Hayashi, M., Clapperton, J., 2007. Distribution of northern pocket gopher burrows, and effects on earthworms and infiltration in a prairie landscape in Alberta, Canada. Applied Soil Ecology 37, 88-94.

Zhou, W., Beck, B.F., Adams, A.L., 2002. Effective electrode array in mapping karst hazards in electrical resistivity tomography. Environmental Geology 42, 922-928.

Zhu, T.X., 1997. Deep-seated., complex tunnel systems - a hydrological study in a semi-arid catchment, Loess Plateau, China. Geomorphology 20, 255-267.

Zhu, T.X., 2003. Tunnel development over a 12 year period in a semi-arid catchment of the Loess Plateau, China. Earth Surf. Process. Landforms 28, 507-525.

Zhu, T.X., Luk, S.H., Cai, Q.G., 2002. Tunnel erosion and sediment production in the hilly loess region, North China. Journal of Hydrology 257, 78-90.

Publication list

Articles in internationally reviewed scientific journals

Verachtert, E., Van Den Eeckhaut, M., Martínez-Murillo, J.F., Nadal-Romero, E., Poesen, J., Devoldere, S., Wijnants, N., Deckers, J., 2011. Impact of soil characteristics and land use on piping erosion in a temperate humid climate. Catena, submitted 17 April 2011.

Nadal-Romero, E., **Verachtert, E.**, Maes, R., Poesen, J., 2011. Quantitative assessment of the piping erosion susceptibility using the pinhole test. Geomorphology 135, 66-79.

Verachtert, E., Maetens, W., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2011. Soil loss rates due to piping erosion. Earth Surface Processes and Landforms 36, 1715-1725.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Govers, G., Deckers, J., 2011. Prediction of spatial patterns of collapsed pipes in loess-derived soils in a temperate humid climate using logistic regression. Geomorphology 130, 185-196.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2010. Factors controlling the spatial distribution of soil piping erosion on loess-derived soils: a case study from central Belgium. Geomorphology 118, 339-348.

Verachtert, E., Govaerts, B., Lichter, K., Sayre, K.D., Ceballos-Ramirez, J.M., Luna-Guido, M.L., Deckers, J., Dendooven, L., 2009. Short term changes in dynamics of C and N in soil when crops are cultivated on permanent raised beds. Plant and Soil 320, 281-293.

Book chapters, internationally recognised scientific publisher

Verhulst, N., Govaerts, B., **Verachtert, E.**, Castellanos-Navarrete, A., Mezzalama, M., Wall, P., Deckers, J., Sayre, K.D., 2010. Conservation agriculture, improving soil quality for sustainable production systems? In: Lal, R., Stewart, B.A. (Eds.), Food Security and Soil Quality. Advances in Soil Science. CRC Press, Boca Raton, FL, USA, ISBN: 9781439800577.

Papers at international conferences and symposia, published in full in proceedings

Verachtert, E., Devoldere, S., Van Den Eeckhaut, M., Poesen, J., Deckers, J. 2010. Impact of land use and soil properties on piping in Belgium. Landform Analysis volume 16, Poznań, in press

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2009. Characteristics and distribution of soil piping erosion on loess-derived soils in Belgium. In: Romero Díaz A., Belmonte Serrato F., Alonso Sarria F., López Bermúdez F. (Eds.), Advances in studies on desertification. Contributions to the International Conference On Desertification In Memory Of Professor John B. Thornes, Murcia, Spain, September 16-19. (ISBN 978-84-9371-888-9) p.435-438

Nadal Romero E., **Verachtert, E.**, Poesen, J., 2009. Pinhole test for identifying susceptibility of soils to piping erosion: methodology and preliminary results. In: Romero Díaz A., Belmonte Serrato F., Alonso Sarria F., López Bermúdez F. (Eds.), Advances in studies on desertification. International Conference On Desertification In Memory Of Professor John B. Thornes, Murcia, Spain, September 16-19.

Verhulst, N., Govaerts, B., **Verachtert, E.**, Kienle, F., Limon-Ortega, A., Deckers, J., Raes, D., Sayre, K.D., 2009. The importance of crop residue management in maintaining soil quality in zero tillage systems; A comparison between long-term trials in rainfed and irrigated wheat systems. In: Proceedings of the 4th World Congress on Conservation Agriculture, New Delhi, India, February 4-7.

Meeting abstracts, presented at international conferences and symposia, published or not published in proceedings or journals

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2011. Impact of soil characteristics and land use on piping erosion - a case study from Belgium. Geophysical Research Abstracts Vol. 13, EGU2011-1590.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Govers, G., Deckers, J., 2011. Susceptibility models for pipe collapse in loess-derived soils in a temperate humid climate. Geophysical Research Abstracts Vol. 13, EGU2011-1591.

Petrlic, K., Nadal Romero, E., **Verachtert, E.**, Bochet, E., Poesen, J., 2011. Spatial patterns of vegetation in sub-humid badlands: a case study from the Central Spanish Pyrenees. Geophysical Research Abstracts Vol. 13, EGU2011-2942.

Poesen, J., Maetens W., Smets, T., **Verachtert, E.**, Vanmaercke, M., Nyssen, J. 2010. Soil and water conservation: problems and research needs for improving predictions. Keynote paper presented at the Environment workshop 2010 on "Optimizing and integrating predictions of agricultural soil and water conservation models at different scales". Universidad Internacional de Andalucia, Baeza, Spain, 27-29 September 2010.

Verachtert, E., Devoldere, S., Van Den Eeckhaut, M., Poesen, J., Deckers, J. 2010. Impact of land use and soil properties on piping in Belgium. In: Zglobicki W. (ed.), Human Impact on Gully Erosion. 5th International Symposium on Gully Erosion, Maria-Curie Sklodowska University in Lublin, Poland, 19-24 April 2010, Book of abstracts (ISBN 978-83-89720-54-2): 122-123.

Nadal-Romero E., **Verachtert, E.**, Poesen, J., 2010. Pinhole test for identifying susceptibility of different horizons in loess-derived soils to piping erosion. In Zglobicki W. (ed.) Human Impact on Gully Erosion. 5th International Symposium on Gully Erosion, Maria-Curie Sklodowska University in Lublin, Poland, 19-24 April 2010, Book of abstracts (ISBN 978-83-89720-54-2): 83-84.

Meeting abstracts, presented at local conferences and symposia, published or not published in proceedings or journals

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J.n 2010. What controls the spatial distribution of soil piping erosion in the Flemish Ardennes, Belgium?. Belgian Geography Days. Leuven, 22-23 October 2010.

Nadal-Romero, E., **Verachtert, E.**, Poesen, J., 2010. Assessing piping erosion susceptibility of loess-derived soil horizons using the pinhole test. Belgian Geography Days. Leuven, 22 - 23 October 2010.

Wijnants, N., **Verachtert, E.**, Martinez Murillo, J., Nadal-Romero, E., Deckers, J., Poesen, J., 2010. Effects of groundwater table positions on the occurrence of soil piping erosion in Central-Belgium. Day of Young Soil Scientists, Soil Science Society of Belgium (SSSB). Brussels, 23 February 2010.

Verachtert, E., Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2009. Spatial patterns for soil piping erosion in the Flemish Ardennes. Day of Young Soil Scientists, Soil Science Society of Belgium (SSSB). Brussels, 25 February 2009.

Govaerts, B., Verhulst, N., **Verachtert, E.**, Kienle, F., Limon-Ortega, A., Mendoza, J., Deckers, J., Raes, D., Sayre, K., 2009. La importancia del manejo de los residuos del cultivo para mantener la calidad del suelo en sistemas de cultivo con cero labranza; Una comparación entre ensayos a largo plazo en sistemas de cultivo de trigo de temporal y de riego. Primer Foro Regional sobre la Quema de Esquilmos. Ciudad Obregón, Mexico, May 2007.

Devoldere, S., **Verachtert, E.**, Van Den Eeckhaut, M., Poesen, J., Deckers, J., 2009. Impact of soil properties on the occurrence of piping erosion. Day of Young Soil Scientists, Soil Science Society of Belgium (SSSB). Brussels, 25 February 2009.